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Photo: A. E. Porsild, 1957.

Fig. 1. Part of the raised bog at the Attawapiskat-Muketei junction, of which the profile is shown in Fig. 7. Beyond the expanse of bog with its large pools several narrowing seepages can be seen. They run into a small brook, dammed by a beaver dam, not visible in the photograph. Some "black-spruce islands" occur near the brook, beyond which is another raised bog.

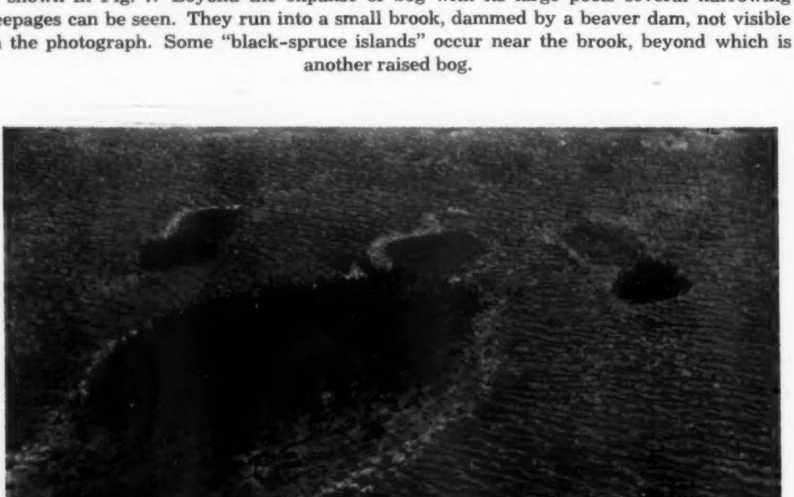

Photo: the author, 1957.

Fig. 2. "Black-spruce islands" in a patterned fen sloping toward the camera. Note the pools up slope from the "islands" and the tail-shaped, drier bog down slope from the larger "island". A sharp change in colour occurs at the "minerotrophic limit". South-southwest of Attawapiskat-Muketei junction.

BOGS AND FENS IN THE HUDSON BAY LOWLANDS

Hugo Sjörs*

THE various types of peatlands differ from one another in many respects. An important factor controlling the composition of peatland vegetation is the origin of the water supply. All peatlands receive considerable amounts of water in the form of precipitation and in some types of peatlands, termed ombrotrophic, precipitation is the only source of moisture and consequently also of mineral salts. Since acids are always formed in peatlands, the scarcity of metal ions in water of precipitation (except in definitely maritime areas) leads to strongly acid reactions both of the water and of the peat in most ombrotrophic peatlands. The vegetation of the ombrotrophic peatlands, or (in a restricted sense) bogs, is highly specialized, acidophilous, and poor in species of flowering plants.

Other types of peatland receive varying quantities of water from mineral soils in addition to precipitation. This water percolates through the surroundings of the peatland and acquires varying amounts of mineral ions in passing through the soil. This minerotrophic peatland is generally termed fen. The minerotrophic influence in the fens always results in a richer and more varied vegetation largely composed of species not present in bogs. This indicates a somewhat better nutritional status and less acid conditions than in the bogs. Some fens are circumneutral and rich in species. Extreme types of these "rich fens" have a high calcium content and abound in calciphilous plants, but there are also fens in which the minerotrophic influence is not sufficient to inhibit the development of a fairly acid reaction; in these the vegetation generally belongs to the "poor fen" type (intermediate between "rich fen" and bog).

Even in regions in which they are extensive, peatlands occur mostly as individual bodies that are confined to depressions. The shapes of the peatland bodies are mainly determined by the configuration of the underlying and surrounding mineral stratum; their hydrotopography is also dependent on climatic factors. Conditions may vary considerably in different parts of the same peatland. For instance, parts of the surface may be ombrotrophic and other parts of it more or less minerotrophic. Such peatland complexes were classified as entities by Cajander in his classic work of 1913.

In a few parts of the world, however, bogs and fens form a continuum, a "peat sea" that is interrupted only by occasional islands of mineral soil, and by lakes and rivers. Extensive tracts that are almost completely

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covered with peat are rare in Europe, where they occur chiefly in Ireland, in the north of Sweden and Finland (unbroken for distances of several, but not very many miles in any direction), in the Polesie, or Pripet lowlands (Kulczyński 1949), and in parts of northern Russia. Similar areas occur in northern Asia and North America. In Canada, in the so-called Hudson Bay lowlands southwest of James Bay and south of Hudson Bay, continuous peatlands extend for a distance of about 800 miles over the flat lowlands formed by sedimentary rocks, from Nottaway and Harricanaw rivers, Quebec, to Churchill, Manitoba. The lowlands area reaches its greatest width of more than 200 miles along the Albany River and almost as much at the Attawapiskat and Ekwan rivers; it becomes narrower to the northwest (Fig. 3).

Much work remains to be done before this vast tract of land can be regarded as well-known, although geographical exploration goes back to the earliest days of the Hudson's Bay Company. The land forms have been described briefly by Coombs (1954); a more comprehensive manuscript by the same author dealing with the geography of the area was, unfortunately, never published (Coombs 1952). Dutilly, Lepage, and Duman (1954) have summarized the floristic data, and Hustich (1957) has contributed a phytogeographical survey. The flora is now being investigated by A. E. Porsild and W. K. W. Baldwin of the National Museum of Canada, Ottawa, and the writer had the great advantage of their company during field studies carried out in 1957.

Air photographs that were studied beforehand, and observations during flights showed a great variability of the configuration of the peatland. However, the individual features of these patterns are often strikingly characteristic and are repeated over and over again (Figs. 1 and 2).

The strange patterns formed by the features are more difficult to interpret than are the features themselves. Some types of pattern recur frequently, but on the whole the patterns are dissimilar and cannot be easily classified into a system of forms of more than local validity. On account of the extreme flatness of the country small differences in the underlying topography and especially in drainage possibilities become decisive factors in peat formation. The direction of the drainage flow is generally easily seen from the air. The type of drainage seems to have a fundamental influence on the configuration of the various kinds of peatland.

The Hudson Bay lowlands have been mapped from air photographs, but the maps give very few figures for altitudes. Little or no information is as yet available regarding the age of the Quarternary deposits, but a few peat cores and samples for radiocarbon dating collected by us may furnish data for one or two localities. The Hudson Bay lowlands were almost completely submerged in post-Pleistocene time and covered with a mantle of marine clay. However, as regards smoothness there is not much difference between the submerged parts and those that are believed not to have been submerged. The highest coastal line (in this area a true "marine limit") is neither visible in the terrain, nor evident on maps or

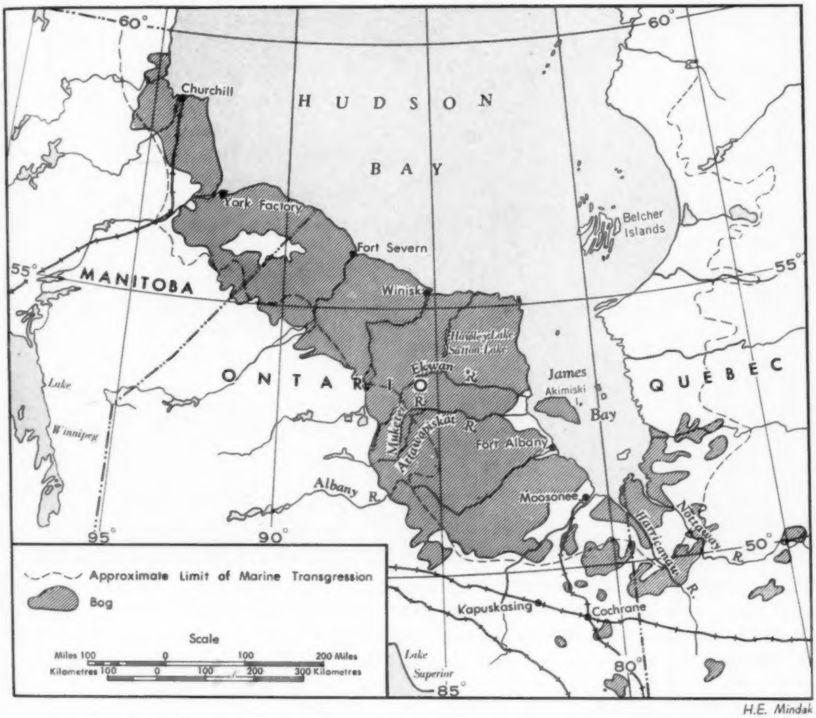


Fig. 3. Sketch map of the Hudson Bay lowlands showing extent of bogs and approximate limit of marine transgression. Based on the 1958 Glacial Map of Canada.

air photographs. Marine shells collected by us indicate that on the Attawapiskat River this line may be farther inland than is indicated on most recent maps; it probably crosses the river at or above the junction with the Muketei. Unfortunately, a reliable figure for the altitude of this point cannot be given.

It is believed that the general slope of the land is about 4 feet to the mile. Most of the country with a distinct slope has strikingly parallel rivers, except in some of the lower regions where there are many former strand-lines, which cause the small rivers to deviate, and sometimes to run parallel to the former shore-line or to follow a zig-zag course. The large rivers have broken through their ancient deltas, and near the coast this process is still going on.

Between the large rivers are extensive flats where the slope is evidently very slight. There the drainage is irregular in direction and much less effective than in the river basins. The fens (and less frequently the bogs) that occupy these flats are exceedingly wet, often containing numerous roundish lakes, which are too shallow for the landing of a plane and are

Fig. 4. Attawapiskat River at its junction with the Muketei River (coming from the right). The banks on the left belong to islands, which consist partly of clayey glacial till and partly of alternating strata of river silt and humus. The higher parts carry tall white spruce; the islands are inundated during extremely high floods caused by ice jams.

inaccessible on foot or by canoe. Thus a close study leading to a better understanding of this area will have to be made from helicopters, or in the fall or winter when the ground is frozen.

Most of the field work done in 1957 was centred on the Attawapiskat-Muketei junction (Fig. 4). This area was selected by Porsild in 1956 on account of its accessibility and the presence of numerous distinct and varied large-scale peatland patterns. In addition, the river banks, cut into calcareous clayey glacial till, provide a variety of plant habitats of floristic and ecological interest.

We chose for our camp the only horizontal and yet not too soft and muddy spot on the clay bank that extends for miles along the Attawapiskat River. The footprints of black bear and sandhill cranes[1] showed the plastic nature of the clay, which is being strongly eroded and is subject to small-scale landslides along parts of the river shore (Fig. 5). Other areas, including the down-stream tails of islands, are covered with willow thickets and show rapid sedimentation.

The higher parts of the islands, as well as the upper edge of the river banks, carry a narrow fringe of tall white spruce *(Picea glauca)*. Large trees, approximately 110 years old, attain a height of nearly 100 feet and

[1]A pair of these birds was later heard, and seen in flight.

Fig. 5. A clay slide at the middle Attawapiskat River. Erosion is cutting back into the bog zone; the zones of white and black spruce that once separated river and bog have already been carried away.

a diameter of 34 inches at breast height. The size and growth rate of these trees, as well as the composition of the flora, show that the climate of the area is boreal rather than subarctic. On some comparatively high flats we found fine stands of aspen *(Populus tremuloides)* with trees up to 70 feet high. At lower levels along the river banks balsam poplar *(P. balsamifera)* commonly grows in dense thickets of alder *(Alnus rugosa* var. *americana* and *A. crispa)*, white birch *(Betula papyrifera)*, red osier *(Cornus stolonifera)*, and willow *(Salix* spp.).[2] This belt is inundated frequently; the lower part, which is covered with willows, is probably flooded every spring. The upper parts of the river banks, about 20 feet and more above summer water-level, seem to be inundated only by infrequent floods that are caused by huge ice jams in the river and may attain extremely high levels. During such exceptional floods ice floes grind against the trunks of white spruce on all but the highest banks. Scars resulting from ice injuries could be dated to 1933 by counting the annual rings. The flood waters of that year left a deposit of silt on the river banks 27 feet above late-July water-level. On the islands as much as 1 inch of unleached calcareous silt was found below a layer of young humus

[2]Cedar *(Thuja occidentalis)* was found on the south bank of the Attawapiskat River at 53°07'N., 85°22'W. Fragments of cedar twigs were frequent in the drift of a tributary from the south at 53°05'N., 85°29'W. This is north of the previously recorded area (cf. Hustich 1957, p. 23).

Fig. 6. Alternating strata of humus and flood-deposited silt in a cutbank, which provides nesting sites for bank swallows and kingfishers. The base consists of glacial till. Island in Attawapiskat River.

and litter, deep inside the stands of black and white spruce that occupy the flat centres of the islands. Still more striking was the fact that grains of the same fine deposit were found on the bark and on the upper surface of twigs of these spruce, up to 7 feet above the ground. A more recent flood that left fine sand grains on young balsam firs *(Abies balsamea)* could be dated to 1945, but was evidently confined to much lower levels.

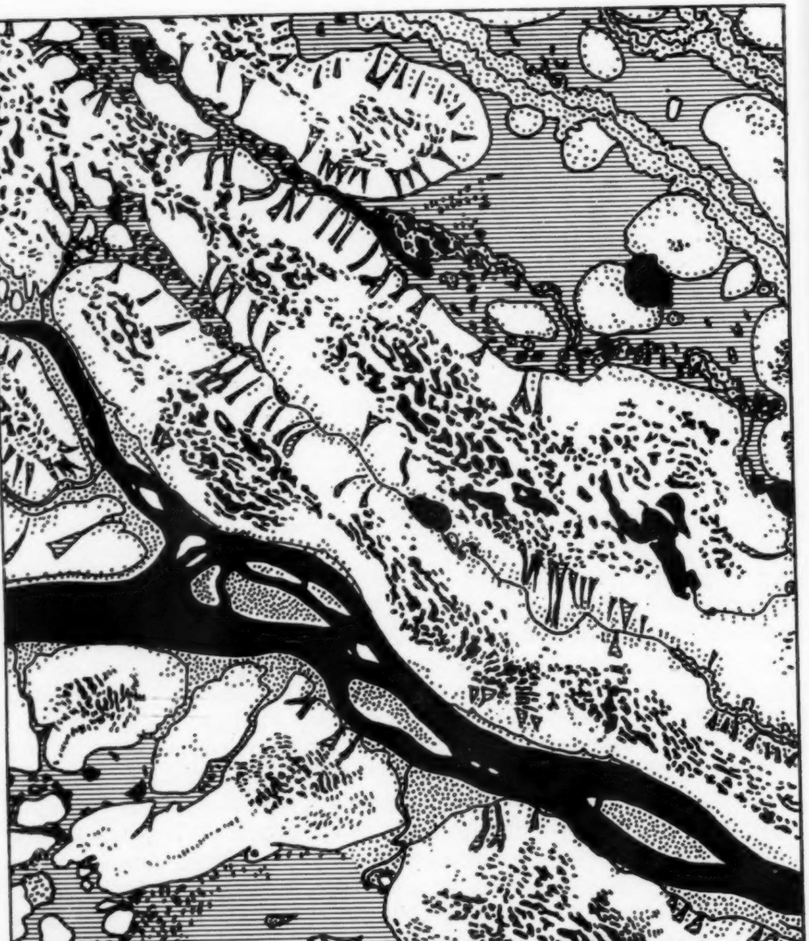
It now became easy to understand the soil profiles found in areas of accumulation, with their alternating layers of fine sand or silt and dark humus (Fig. 6). The alkaline river silt and the forest litter (evidently rich in nitrogen) create a fertile soil that is conducive to luxuriant plant growth. This is most evident at levels below that of the spruce forest, in places where the shade is not too deep for herbs like *Solidago gigantea, Thalictrum dasycarpum, Heracleum lanatum, Eupatorium maculatum, Apocynum sibiricum,* and *Anemone canadensis.* In a region with longer summers similar soils would have their stratification disturbed by earthworms.

The region has a slight but regular gradient, and the creeks generally parallel the Attawapiskat, dividing the country into comparatively regular, narrow strips. The streams are fed by drainage from either side. This is an ideal situation for the development of ridge-shaped raised bogs on the strips between the streams (Fig. 7). In Sweden similar bogs occur in

corresponding situations even north of the "climatic limit" of raised bogs postulated by Granlund (1932). Air photographs of the Attawapiskat ridge-shaped bogs were strikingly similar to some known to me from northern Sweden, although in their regularity, their large size, and multitude of oft-repeated features, the ridge bogs of the Attawapiskat surpass those of Sweden. The particular Attawapiskat bog that was studied by us shows evidence that during its development sedimentation from river floods occurred only at a very early period, and that the growth of the peat soon raised the surface beyond the reach of the highest waters (Fig. 8). The present acidophilous vegetation, as well as the pH values, show this quite clearly.

Except in some regions that have a strictly maritime climate, the surfaces of large bogs develop an undulating topography of hummocks and depressions, of which the last-named are termed hollows. Both features are covered with distinct plant communities, each of which is strictly confined to a definite ecological situation that is characterized by peat growth and structure, water-level, etc. As previously stated, the plant communities of the Attawapiskat bogs correspond almost exactly to those found in regions of northern Europe that have a non-maritime climate, especially in Sweden and Finland. This very remarkable similarity of the vegetation in regions 3,500 miles apart is chiefly due to the fact that both regions have practically identical cryptogamous floras, and that in both nearly all cryptogamous species have similar ecological requirements. As to vascular plants, the flora of the peatlands has a higher percentage (about 50 per cent) of species that are found in both regions than that of the mineral soil. Again, the species common to both regions have, with few exceptions, almost identical ecological requirements. Some of the vicarious species of one region are closely related to those of the other, but they frequently show ecological differences. For instance, *Eriophorum spissum* of eastern North America is mainly confined to hollows, evidently because it lacks the extreme toughness and capacity for elongation of the basal parts that make it possible for *E. vaginatum* to persist during the hummock stage in the cyclic succession known to take place in European bogs. Other more important differences in the hummock communities are due to the absence of *Pinus silvestris, Betula nana,* and *Calluna vulgaris* at Attawapiskat, where the place of these species is taken by *Picea mariana, Ledum groenlandicum,* and *Chamaedaphne calyculata,* of which only the last occurs in eastern Fennoscandia. *Ledum palustre* of Fennoscandian pine bogs is less common in open bog than is *L. groenlandicum* of North America. To a European botanist, of course, the presence of such American endemics as *Carex oligosperma, Eriophorum virginicum, Sarracenia purpurea, Utricularia cornuta,* and the bog laurels *(Kalmia polifolia* and *K. angustifolia)* is of special interest. It was astonishing to discover here the amphi-Atlantic *Rhynchospora alba,* far beyond its previously known range.

The most striking feature of these bogs is the large bog pools. These bodies of clear brownish water occupy the greater part of the surface



Based on an R.C.A.F. air photo.

of large expanses of bog. With a uniform depth of 5 feet they reach only about half-way through the peat; they were therefore formed much later than the bogs themselves. Like the ordinary hollows, only much larger, they are oriented at right angles to the directions of the slope of the bog surface. On the highest, central part of the bog ridge they show a more irregular shape (Figs. 1 and 7). Differences in level of a few inches (Fig. 8) regulate the shape of these bog pools, which may be as much as half a mile in length. In bogs in which the pools are very extensive they receive comparatively small amounts of acid water from *Sphagnum* and peat and may be regarded largely as rain-water basins.

On limited parts of the bog expanses a higher pH value may be found and also a few species of fen plants, most frequently *Menyanthes trifoliata*. Fissures in the peat caused by seasonal frost heaving are often found in the hollows of these sites. Thus the highly calcareous subsoil about 10 ft. below the surface may have a slight influence on the water (Fig. 9).

The centres of these raised bogs evidently have a very limited run-off, for we saw no drainage channels on the central bog expanses. At the edges lateral seepages take the form of strips of fen that run down the slope at right angles to the edge between slightly elevated tongues of dry black-spruce muskeg. Each of the seepages, which become gradually narrower as they extend down-slope toward the bog edge, consists of a series of small, shallow pools in a stepped arrangement. The seepages appear rather similar to some types of fen found both in this region and in northern Fennoscandia, where the shallow pools are called *flarks* or *rimpis*. The moving water in the seepages comes from the bog. Nevertheless, the water can hardly be regarded as ombrotrophic, because it has a distinctly higher pH value than that of the bog proper. Fen plants occur in the seepages in greater numbers than in the above-mentioned sites with fissures on the bog expanse, even forming patches of true fen vegetation along the rows of flarks. A condition that may add to the saturation of the peat with metal ions and to the nutrient take-up of the plants in the seepages is the fact that the water is moving down-slope more rapidly than on the central expanse.

A few water samples were analyzed chemically. The concentration of mineral ions in raised bogs was very low in contrast to strongly calcareous

Fig. 7. Map of the surroundings of the confluence of Attawapiskat and Muketei rivers (coming from the northwest). In the former are numerous stream-lined, more or less forest-covered (indicated by dotting) islands. Northeast of the river extend two parallel ridge-shaped bogs with numerous bog pools and many tapering seepages leading to the small brook between the bogs. The southwest and northeast parts of the map show large fens (indicated by horizontal hatching) and slightly raised bogs of various shapes (indicated by encircling solid lines). Densely dotted small bog areas are "black-spruce islands". Note almost continuous rows of these along two brooks in the northeast corner. Note also small bog "tails" down slope (toward the east) of "black-spruce islands" in the large fen southwest of the river. Only large pools are shown, the innumerable "flarks" in this fen are too narrow and too closely crowded for small scale mapping.

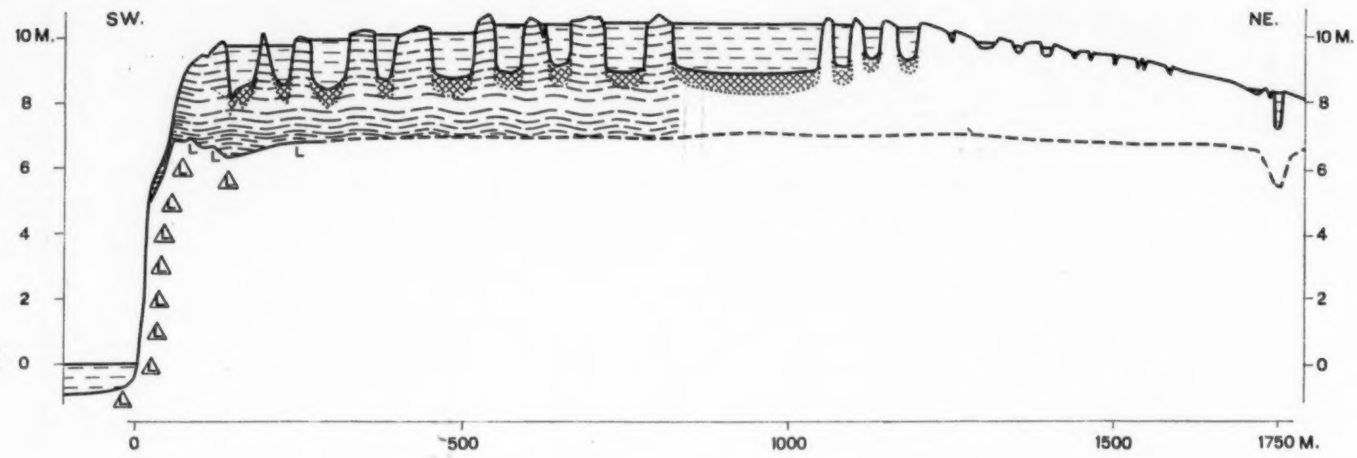


Fig. 8. Profile across the raised bog ridge between Attawapiskat River and the nearest brook, obtained by levelling. The bog rests on a plateau of clayey glacial till (indicated by L's in triangles), which is overlain locally by marine clay (indicated by L's) and in depressions also by river deposits. The bog slope facing the river carries a dense forest of black spruce. Between the pools the black spruce are low and scattered. Thin deposits of coarse organic detritus (indicated by cross hatching) cover the pool bottoms. The lower part of the *Sphagnum* peat is more humified and contains more wood than the upper. On the right the profile follows a seepage cutting several small "flarks". The thickness of the peat deposit was measured only in the left 300 metres of the profile, in the remainder it is conjectural. Vertical exaggeration 50:1.

Fig. 9. Bog on the middle Attawapiskat River with a rather atypic hollow. Frost heaving has lifted parts of the peat from the bottom of the hollow and killed some of the *Menyanthes* rhizomes. This plant is usually confined to fens (both "rich" and "poor"), but in this site it was probably favoured by local chemical influences that extended from the calcareous subsoil through frost cracks.

conditions elsewhere. A single sample from a seepage had a slightly higher mineral content than water samples from the bog. However, a great many more analyses are required in order to reach an understanding of the hydrochemistry of the bog.

Owing to lack of time and difficulties of access little attention could be given to the study of other types of peatland. There are wide expanses of fen in the area. Except in local riparian fens their surfaces are beyond the reach of floods. In spite of almost total absence of exposed mineral soils from which it could come, the water that moves slowly down slope through them is strongly minerotrophic. It is probable that mineral ions are acquired from deeper strata in some way as the water percolates through the fens. Besides larger pools a succession of low ridges and flarks at right angles to the direction of the slope is often seen in the fens (Figs. 2 and 10). The ridges and flarks are only a few yards wide and are repeated endlessly. Scattered low tamarack *(Larix laricina)* and dwarf birch *(Betula pumila* var. *glandulifera)* grow on the low ridges. In the flarks are found such fen species as *Utricularia vulgaris*, *U. intermedia*, and *U. minor*, *Carex livida*, *C. chordorrhiza*, and *Juncus stygius*. This entire flora is clearly similar in type to that of the "rich fen" or "brown fen" of Fennoscandia. The moss flora, which includes *Scorpidium scorpioides*,

Photo: A. E. Porsild, 1956.

Fig. 10. A large fen with narrow "flarks" and low ridges at right angles to the direction of the slope, which is to the bottom left corner.

several species of *Drepanocladus*, and *Campylium stellatum*, is practically identical, as are vascular plants, such as those mentioned above as growing in the flarks, and *Trichophorum alpinum* (= *Scirpus hudsonianus*), *Carex tenuiflora*, *Selaginella selaginoides*, and *Tofieldia pusilla*, that occur mainly on the low ridges. American species, characteristic of "rich fens" are numerous, e.g. *Tofieldia glutinosa*, *Drosera linearis*, *Salix pedicellaris* var. *hypoglauca*, *Carex leptalea*, *C. gynocrates*, *C. lanuginosa*, *Eriophorum viride-carinatum* (vicarious for *E. latifolium* of Europe). A real gem of the fens is the American orchid *Arethusa bulbosa* with a large red flower, which looks very strange in these surroundings. *Triglochin maritima*, which is mainly a sea-shore plant in Europe, is quite common in the "rich fen" and on wet, calcareous riverbanks. In various calcareous sites (less frequently in peat-forming fens) *Carex scirpoidea* is common, whereas in Europe it is one of the rarest and most highly specialized plants and is known only from a single station in the Norwegian mountains.

Roundish "black-spruce islands" had been noted on air photographs and during earlier flights over the lowlands as conspicuous features, scattered over the large fens, and forming more or less continuous belts along small streams. Some of the "black-spruce islands" gradually collapse along the edges, as is shown by a fringe of dead trees. The "islands" may also burn. Some are ring-shaped with a wet, treeless centre (Fig. 11). Most

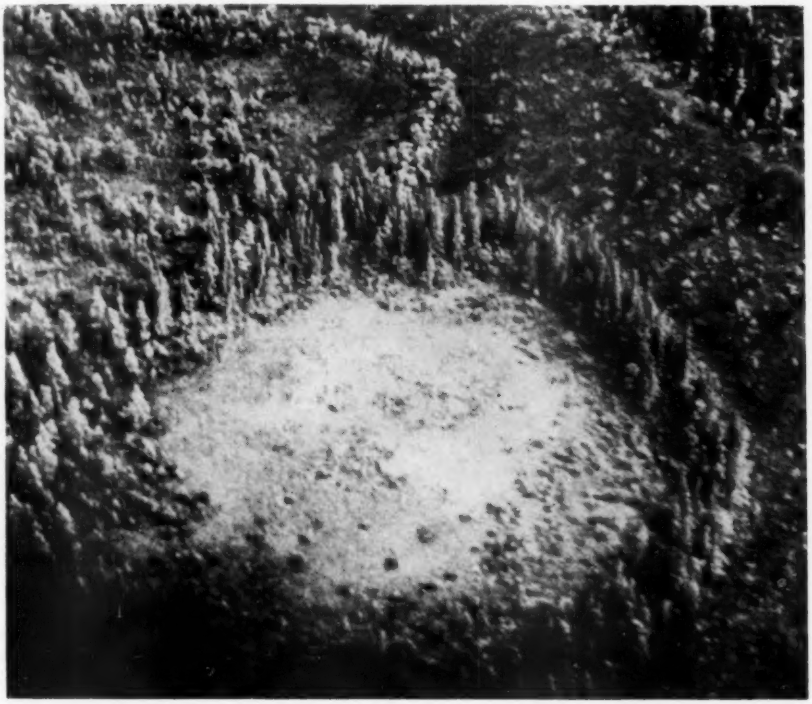


Photo: A. E. Porsild, 1956.

Fig. 11. Ring-shaped "black-spruce islands" in a fen.

areas with such "islands" can be reached on foot only with difficulty. However, one "island" was reached in a fen south of Attawapiskat River; it was horseshoe-shaped, 1/6 mile in diameter and its highest point was estimated to be about 7 feet above the surrounding fen. It had steep sides and was completely covered with a stand of black spruce. A pit was dug through 2 feet of highly humified black peat containing a *Sphagnum* layer, although *Sphagnum* is absent from the present surface vegetation, which consists mainly of *Ledum groenlandicum*, the moss *Pleurozium*, and the lichen *Cladonia rangiferina*. At a depth of 26 inches permafrost was struck. There is little doubt that these "black-spruce islands" have raised cores of permafrost, which is otherwise completley lacking in the southern area. The ice cores found in some of the ordinary bog hummocks probably disappear in late summer.

Farther north, for instance near Sutton and Hawley lakes southeast of Winisk, knolls of a different type, which also have cores of permafrost, were found. This region is well covered with trees that form a forest, chiefly of black spruce, which is distinctly subarctic rather than boreal in

Fig. 12. Side of a 9-foot palsa. Above the snow-level the branches of the black spruce are conspicuously worn by the prevailing northwest winds. Palsa bog west of Hawley Lake. The peat-borer case, used to indicate the scale, is slightly over 1 metre long.

appearance. In some bogs, these numerous small but fairly high knolls are of a type quite similar to the *palsas* of subarctic Europe. Only scattered small black spruce and tamarack grow on these palsas. Their summits are bald, covered only with wind-resistant lichens such as *Cetraria nivalis*. The highest palsa seen was nearly 9 feet high. By the end of June no ice remained in the wet peat between the palsas, in the fens, and in the mineral soils and only thin seasonal ice in the peaty forest soils. Permafrost is thus restricted to the palsas, even in this more northern region (Figs. 12 and 13).

An important part in the history of paludification of the region is played by the beaver. Beaver dams may raise the level of peatland along streams and lakes considerably and repeatedly. On the other hand, numerous small lakes are obviously old beaver ponds that were perhaps enlarged by wave action and ice push, which may explain their roundish outlines. The action of the beaver, once common but now almost extinct in Europe, must have had a similar effect on the development of lacustrine and riparian fens in the Old World, a factor that seems to have been largely overlooked there, but which was noted in Canada by the explorer David Thompson about 150 years ago (Tyrrell 1916).

The writer, accompanied by his wife as assistant, spent 6 weeks in the summer of 1957 in the Hudson Bay lowlands. He wishes to express

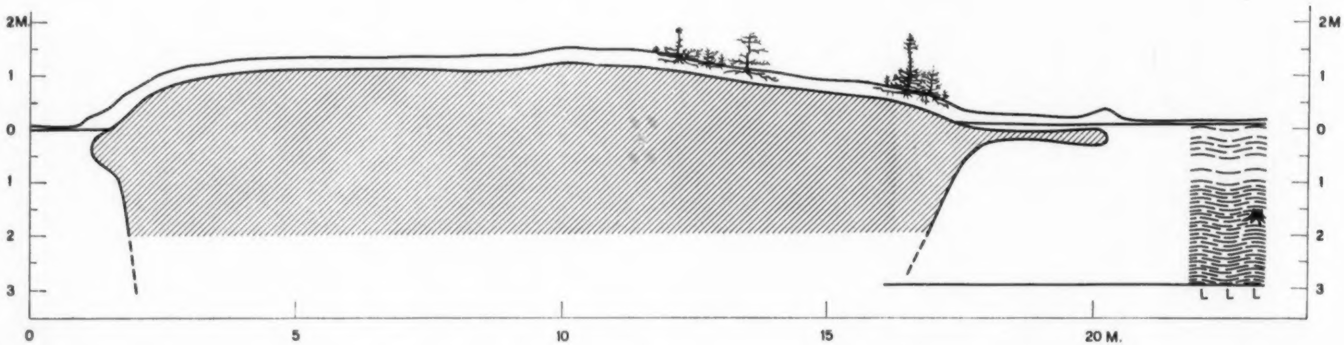


Fig. 13. Section through the body of a medium-sized palsa in a bog west of Hawley Lake, June 30, 1957. The frozen core is indicated by hatching. The roots of black spruce and tamarack are confined to the dry surface peat, which is mainly covered with whitish lichens. Note that the sides of the frozen core slope inward. It appears likely that the frozen core of the palsa extends below the peat into the underlying clay (indicated by L's). The thin layer of frost in the peat beneath cushions of *Sphagnum fuscum* on the right is seasonal only. The *Sphagnum* peat surrounding the palsa is very soft near the surface; its lower strata are dense, highly humified and contain spruce wood. The profile of this peat was unfrozen, continuous, and undisturbed, down to the clay on which the bog rests. The bog is sloping slightly, so that the water-level on the right side of the palsa is 8 cm. above that on the left. No vertical exaggeration.

his deep gratitude to Dr. A. E. Porsild, Chief Botanist, National Museum of Canada for an invitation to join the field party led by him, as well as to Mr. W. K. W. Baldwin, Assistant Botanist. His sincere appreciation is expressed also to the Ontario Department of Lands and Forests for air transportation in the field, and to the Arctic Institute of North America for a grant from the Banting Fund, which made his participation possible.

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SOME STRUCTURAL AND THERMAL CHARACTERISTICS OF SNOW SHELTERS

Robert W. Elsner* and William O. Pruitt, Jr.†

Introduction

The current rapid expansion of long-range aircraft operations, both military and civilian, into arctic regions suggests the need for critical appraisal of techniques and equipment required for survival problems and emergency shelter construction in extreme cold. The need for practical, easily built shelters is apparent in many arctic activities, such as mid-winter travel and military manoeuvres. The use of naturally occurring compacted snow as a structural material for dwellings has a long history, principally among the Eskimo of the Central Canadian Arctic. Stefansson (1944) and others (Mathiassen 1928, Birket-Smith 1929, Rowley 1938, and Browne 1946) have described Eskimo tools and methods for the construction of the familiar, domed snow-block house. Relatively little is known, however, concerning the thermal and structural properties of snow shelters.

Some temperature measurements taken at various levels inside a snow house during occupation have been recorded (Stefansson 1944, Mathiassen 1928). Koppes (1948) discussed some theoretical aspects of the thermal characteristics of the snow house and, making several assumptions, estimated the heat required to maintain a temperature difference of 50°F between inside and outside air. He calculated that the metabolic heat of four occupants was enough to sustain such a temperature difference in a house with the following characteristics: domed snow-block construction with door and entrance trench built on a lower level than the shelter floor, forming a "cold trap", interior volume 410 cubic feet, floor diameter 11 feet, average wall thickness 9 inches, thermal conductivity for compact snow 1.48 BTU/in./ft.^{2}/hr./°F (Handbook 1950), outside air movement 25 miles per hour, and one air change per hour by diffusion through the open door without roof ventilator. This estimate confirms the casual observations of those familiar with such shelters as regards their remarkable ability to protect from wind and low air temperatures. Koppes also reports a suggestion of Sir Hubert Wilkins for the construction of snow houses with unconsolidated snow by using a pneumatic form. This would provide an

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extremely simple technique requiring little experience or skill and would considerably extend the availability of snow as building material.

The possible influence of arctic microclimates on the thermal characteristics of snow houses is suggested by the recent work of Johnson (1954) and Pruitt (1957). These studies indicate the substantial advantage that can be gained by using the existing heat flow from the relatively warm ground outward through the snow cover. Temperature measurements at the subnivean ground surface in the spruce forests of interior Alaska were reported to be in the neighbourhood of +20°F to +25°F These temperatures are remarkably stable even with snow depths as small as 1 foot and with air temperatures at the snow surface as low as —55°F. Subnivean ground temperatures appear to vary considerably with the character of the ground surface, being highest over moss and grass and lowest over gravel, but they are nearly always well above outside air temperatures. Similar, though smaller, thermal gradients exist in the snow cover over arctic tundra (Johnson 1954) and sea ice (Holtsmark 1955). Temperatures at various depths in a permanent antarctic snow-field were measured by Wade (1945). At a depth of 4 metres they were found to remain essentially constant at approximately the same value as the mean annual air temperature. It has been frequently noted in arctic regions that temperatures in valleys or hollows are generally lower than on nearby hills or ridges. The difference may amount to 20° to 30° F in the absence of wind. The disadvantage of building a shelter in a valley bottom or of sleeping in a simple hole in the snow is apparent.

The practical use of these arctic microclimates becomes important when fuel must be conserved or is not available. Success in the use of the ground heat to raise the temperature of a shelter requires that it is well insulated. Snow is an abundant, efficient insulating material. Its use can give a very considerable thermal advantage so that survival will be possible with a minimum of clothing and equipment in the relatively warm interior of an efficiently constructed shelter. The use of an entrance "cold trap" or adequate door of snow-block or other construction is, of course, essential.

Shelter construction using compacted snow

During the winter of 1955-6 the feasibility of snow-shelter construction using loose, unconsolidated snow as building material was studied. Experimental shelters were built near the River Laboratory of the Arctic Aeromedical Laboratory, Ladd Air Force Base, Fairbanks, Alaska. The Fairbanks region has a typical interior Alaska climate with extreme cold and little wind in midwinter. The snow is rarely compacted by wind and is generally unsuitable for cutting snow blocks or digging snow caves. Snow depth during the winter ranges roughly from a few inches to 2 or 3 feet. Average density is of the order of 0.2 gm./cm.^{3}.

Browne (1946) suggested a method for rendering snow of this type fit for cutting blocks by tramping a suitable area with ski or snowshoes and

then allowing the area to remain undisturbed for a few hours or over night. However, the compacting and settling process requires several hours and the resulting blocks are frequently very fragile and non-homogeneous. Birket-Smith (1929) mentioned tramping soft snow to compact it. He also described a dome-shaped, temporary Eskimo shelter consisting of bent branches covered with skins and a layer of loose snow thrown over the outside.

Several experimental shelters were built by the method suggested by Wilkins (Koppes, 1948) using a weather balloon inflated to approximately 4 feet in diameter. The construction procedure was as follows:

(a) excavating a hole in the snow to the ground of sufficient size to take the balloon;

(b) shovelling snow from the surrounding area over the balloon to a depth of about 1 foot;

(c) leaving the shelter undisturbed for at least 1 hour;

(d) excavating a hole on one side, deflating the balloon, and further digging out the interior as required;

(e) making a door of snow blocks, garments, or other available material.

The interior of such a shelter can be glazed to increase its strength, if desired, by raising the temperature inside with a suitable stove.

The use of a weather balloon or similar pneumatic form is not indispensable for this type of construction. Similar shelters were built by using a parachute laid over a pile of spruce and willow branches and small trees. Survival kits, aircraft fragments, etc., would serve just as well. Even these are not necessary, only more time and work is required to pile up and excavate a snow mound. No skill or special tools are needed, snowshoes or hands can be used for shovelling. The Nunamiut Eskimo of the Anaktuvuk Pass region of northern Alaska are familiar with this type of construction. Osgood (1936) has described a similar emergency snow shelter used by the Kutchin Indians of northwestern Canada.

The success of this general method depends on a type of artificial compaction known as *depth processing* (Taylor 1953), the existing thermal gradient in the snow cover is disturbed and the snow is thoroughly mixed by being shovelled. Shakhov (1948) discussed the "sublimation-thermodynamic theory" as the most probable way of accounting for consolidation within a snow cover in the absence of wind. The change in hardness is presumed to be dependent on the sublimation of water vapour adjacent to snow crystals of relatively high temperature and its subsequent recrystallization on snow crystals of lower temperature. This [cementing] process, which takes place slowly in a natural snow layer, proceeds very much faster following disturbance and mixing when many "cold" and "warm" snow particles are placed close to each other and the snow of the whole layer is exposed to the relatively low temperature of the air above. This is followed by rapid recrystallizing of water vapour and cementing of the particles. Table 1 illustrates the thermal conductivity of snow as compared with various other insulating materials.

Table 1. Thermal conductivity of snow compared with that of various insulating materials.

	Density gm./cm.^{3}	*Porosity per cent air*	*Thermal Conductivity (cal./cm.*^{2}*/sec./°C./cm.)* $\times 10^{-4}$
Snow	0.39	57.5	6.4
	0.28	69.5	2.49
	0.14	84.7	1.52
Brick	—	—	15*
Dry soil	—	—	3.3*
Sawdust	—	—	1.2*
Rock wool	—	—	0.94*

The figures for porosity are from Bader *et al.* (1939).
Thermal conductivity values for snow are from Yosida and Iwai, cited by Mantis, (1946).
* Handbook of Chemistry and Physics, 32nd edition, 1950-1.

A detailed record of the changes in density and hardness was obtained during the construction of one such shelter on February 28, 1956. The snow depth was 31 inches. The lowest 6 inches consisted of depth hoar. The average density was 0.22 gm./cm.^{3}. "Hardness" (yielding pressure), measured with a Canadian Snow Test Kit[1] hardness gauge, ranged from 8 gm./cm.^{2} to 80 gm./cm.^{2}. Air temperature at 3 feet above the snow surface was —17°F.

A weather balloon was covered with snow and left undisturbed for 4 hours. The density of the snow in the wall of the completed house was 0.28 gm./cm.^{3}. Hardness varied greatly from place to place, sample figures ranged from 200 gm./cm.^{2} to 850 gm./cm.^{2}, but the rapid changes accompanying the compaction process are indicated by these values. Snow of these physical characteristics is fit for structural purposes. The final thickness of the wall was 14 inches at the top and approximately 3 feet at the base. The interior ceiling height was 4.5 feet. Floor diameter was 6 feet.

Thermistors were installed in this shelter immediately after construction and positioned 4 inches below the ceiling, at the centre of the interior, and 4 inches above the floor. The floor was carefully cleared of snow, exposing the sod of the ground surface. The door was sealed with snow and temperatures were read within 10 minutes, the time then being 1530. Typical temperature measurements taken in the unoccupied shelter and its environs are listed in Table 2. It can be seen that the interior temperatures attained rough equilibrium with the ground surface temperatures during the period of observation. The air temperatures of the interior remained nearly constant for a range of outside air temperatures from —12°F to —40°F. This represents a maximum temperature difference of 60°F. It is clear that a considerable thermal advantage is gained in a well-built snow shelter without artificial heating even during periods of extreme cold when maximum use is being made of ground heat.

During occupancy of a snow shelter of this type for a period of 11 days temperatures were measured at various times, using an alcohol thermometer. They are listed in Table 3, for the contents of which we are indebted

[1] Committee on Snow and Soil Mechanics, N.R.C., Ottawa, Canada.

to Dr. Horace F. Drury, Arctic Aeromedical Laboratory. The door of this shelter consisted of the canvas pack of a discarded back-type parachute. Temperatures were measured 4 inches above the floor.

Snow-block construction

Some observations were made on domed shelters constructed of snow blocks on the sea ice about 5 miles from shore near Barter Island, Alaska, in April 1956. Two snow-block shelters were constructed, one directly on the sea ice after clearing away 4 inches of snow, and the other on a drift about 18 inches deep. The blocks were cut from an 18-inch drift of snow having a density of 0.39 to 0.46 gm./cm.^{3}, and a hardness of about 80 to 200 gm./cm.^{2}. One inch of depth hoar was found at the bottom of the snow-drift. The best snow for block-cutting had a density of about 0.30 to 0.35 gm./cm.^{3} and a hardness of about 150 to 200 gm./cm.^{2}, but such snow was relatively rare. Both an ordinary carpenter's saw and a standard Air Force survival saw were used with equal ease. Block dimensions were 20 by 12 by 6 inches. Interior dimensions were 7 feet in diameter at the floor by 5 feet high from floor to ceiling. Both shelters were constructed without attempting to include a below-floor-level entrance. Cracks between blocks were plugged with loose snow both inside and out. Doors consisted of snuggly fitting snow blocks.

The prevailing ambient air temperatures were not sufficiently low to provide a rigorous test of the effectiveness of these shelters, but some observations are of interest (Table 4). All temperatures were recorded with shelters unoccupied and doors sealed, except as indicated. Thermistors were mounted 6 inches below the ceiling, 4 inches above floor level and in the centre of the shelter.

The data of Table 4 suggest that the subnivean microclimate on arctic sea ice can be used to provide a relatively warm dwelling. In addition to the conventional domed snow houses a trench was constructed by digging into a drift to a depth of 2.5 feet. Its length was 7 feet and the width 2.5 feet. The roof was made of horizontal snow blocks. With one occupant and a snow-block door the interior temperature at sleeping level, 6 inches above the floor was 20° to 24°F. It was surmised, but not experimentally verified, that the snow trench was a more efficient shelter than the domed houses. It had not such high convective heat losses by wind and was probably better insulated by virtue of its much thicker walls.

Discussion

The observations described show that the main advantage of snow shelters stems from the fact that an insulated air pocket is warmed by heat derived from the heat reservoir of the earth.

In spite of the relatively high inside temperatures of the shelter as compared with those of the outside air the occupants can still loose considerable

Table 2. Temperatures of unoccupied snow shelter and environs (°F.).

Date and time	*Outside air 3 ft. above snow surface*	*Ground surface beneath undisturbed snow, 20 ft. from snow shelter*	*Interior of snow shelter*		
			Top	*Centre*	*Floor*
Feb. 28, 1956 1530	−17	+19	+16	+18	+16
Feb. 29, 1956 0815	−36	+20	+20	+20	+19
March 1, 1956 0800	−40	+19	+18	+18	+19
March 5, 1956 0800	−36	+16	+16	+16	+16
1630	−12	+17	+15	+16	+16

Table 3. Inside and outside air temperatures of snow shelter (°F.). Measurements taken at various times during an 11-day period.

Conditions	*Outside temp.*	*Inside temp.*
No door, unoccupied for several hours	+4	+8
No door, unoccupied for several hours	−2	+7
Canvas door in place during the following measurements:		
Unoccupied	−7	+14
Unoccupied for 2 hours, 1 candle burning	−14	+21
Two occupants, plus a 2nd candle, for ½ hour	−14	+24
Two occupants overnight	−2	+21
One occupant	−49.5	+20
Unoccupied for several hours	−28	+14
Two occupants, 2 candles, for 15 minutes	−48	+23.5
Two occupants overnight	−55	+19
Unoccupied	−38	+14
Unoccupied, 1 candle	−42	+18
Morning, 2 occupants overnight	−10	+19
Unoccupied for several hours	−1	+15
Two occupants, 2 candles, for 15 minutes	−3	+24
Unoccupied for several hours	+7	+19
Unoccupied for several hours	+10	+18

Table 4. Temperatures of domed snow-block shelters and environs (°F.).
Shelter No. 1. built directly on sea ice.
Shelter No. 2 built on snow-drift 18 inches deep.

Date and time	*Shelter number*	*Outside air temperature*	*Wind m.p.h.*	*Subnivean temperature**	*Interior of shelter*		
					Top	*Centre*	*Floor*
Apr. 17, 1956 1930†	1	−5	14	+16	+10	+7	+7
Apr. 19, 1956 1915	1	−2	6	+17	+12	+11	+10
	2	−2	6	+17	+10	+9	+8
	2	(with 1 occupant, door closed)			+19	+20	+18

*At the surface of the sea ice beneath 14 inches of snow.

† One hour after construction.

amounts of heat. Since there is probably little convection inside a shelter the major avenues by which an occupant can loose heat are radiation to the walls and conduction to the floor. With respect to the radiation from the surface of a clothed person snow is essentially a black body. Heat losses by this path could therefore be reduced by shielding the walls. The most effective shield would be a material of low emissivity, such as aluminium foil, but a cloth lining would help materially and is more likely to be available. If the cloth has an emissivity in the infrared region close to unity (essentially a black body) and the temperature difference between inner and outer surfaces is slight (a few degrees), heat loss by radiation will be significantly lowered, depending as it does on the difference of the fourth power of the absolute temperatures of the radiating surfaces. A liner has the additional advantage of reducing glazing of the walls and subsequent loss of insulating efficiency. A cloth liner for snow houses has been described by Turner (1941) and the use of a skin liner for houses by Eskimo by Mathiassen (1928).

Heat loss by conduction to the floor can be reduced by the use of available insulating materials under the sleeping bags. Caribou-skin sleeping pads have, of course, a long history. Heat loss is relatively high when an air mattress alone is used, probably because of convection and radiation losses through the mattress. This can be substantially reduced by placing clothing or other insulating material between sleeping bag and air mattress.

When a snow shelter is heated with a pressure stove ventilation becomes necessary. The hazard of carbon monoxide poisoning can be serious in a poorly ventilated shelter, particularly if the interior has become well glazed. The simple expedient of making a hole in the roof and opening the door is usually sufficient. Stefansson (1944) has described methods of ventilation. The factors involved in carbon monoxide poisoning in snow shelters have been discussed by Henderson and Turner (1940); Irving, Scholander, and Edwards (1942); and Scholander, Irving, and Edwards (1943).

Whereas most of the comments of this discussion apply particularly to regions of extreme cold, the snow house is not without virtue in more temperate climates. The snow cover in the Cascade Mountains of Washington, for example, is very deep and has a relatively small temperature gradient. The snow is often suitable for snow-block or cave construction. The air temperatures are generally a few degrees below freezing and occasional periods of thaw occur. Building snow shelters and living in them is therefore sometimes an unpleasantly wet occupation. With carefully insulated floors and the use of liners snow-block shelters or snow caves can be excellent even in this climate.

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RECENT STUDIES OF THE NORTH MAGNETIC DIP POLE*

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Introduction

THE Division of Geomagnetism of the Dominion Observatory is often approached for information on the north magnetic dip pole and its motions by cartographers, students of geomagnetism and aeronomy, and individuals or institutions interested in the Arctic. The authors have recently re-examined the relevant scientific data available to them in order to provide the best possible estimate of the secular motion of the dip pole, and consequently to determine its position for the world declination charts, epoch 1960.0. The opportunity is taken to comment on the geophysical significance of the dip pole and its secular motion.

Pole determinations prior to 1950

Madill (1948) has described determinations of the position of the north magnetic dip pole by Ross and Amundsen, and outlined some of the results of the post-war arctic surveys carried out by this Division. The successive surveys, "Operations Magnetic" made in co-operation with the R.C.A.F., were discontinued after the 1950 field season. Hutchison derived the mean position of the pole for epoch 1950.0 in excellent unpublished work on the reduction of the results from these arctic field stations. To do this he constructed a chart of the two horizontal components of the earth's field, obtained by resolving the total horizontal intensity parallel and perpendicular to the Greenwich grid direction at any point (*see* Appendix). The two components U (grid-north component) and V (grid-east component) were plotted on polar stereographic projection and contoured graphically, using for interpolation and adjustment the orthogonal relation $dU/dv = dV/du$, which holds approximately at high latitudes. Small u, v are parameters of position. This relationship can be derived from Maxwell's equations by assuming that the contributions to the surface field from sources external to the earth are negligible (Hutchison 1949). The pole is located at the intersection of the U = O and V = O contours. The reduced data from surveys carried out prior to 1950 by the Dominion Observatory give

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a somewhat indefinite intersection point, and the best estimate of the position for epoch 1950.0 was 74°N., 100°W. This position was derived after correcting the field station data for diurnal variation and the data from different years for secular variation. However, the presence of undetected crustal anomalies in the earth's magnetic field and the unknown annual variation could make this an erroneous estimate. After examining the magnetograms of the magnetic observatory at Resolute, Cornwallis Island, only some 100 miles from the dip pole, we now know that systematic errors caused by the observations having been made mostly in July and August are probably less than about 5 miles. The effect of undetected crustal anomalies is more difficult to assess. The average density of magnetic field stations within a few hundred miles of the position of the dip pole is one station per 7,000 square miles. Using the curves published by Serson and Hannford (1957), (which refer to more southerly latitudes and show the root mean square errors in magnetic charts produced by linear interpolation between field stations), we have estimated that the uncertainty in the pole position is $\pm 1.2°$ in longitude and $\pm 0.6°$ in latitude. However, this result is only true in a statistical sense. It ignores the differences in geological structure between the Arctic Archipelago and other regions, and neglects the use of the orthogonality relationship mentioned above as an aid to mapping. We consider it likely that these estimates are too high, and experimental observations described below certainly suggest that near the dip pole the effect of anomalies is not too serious. Rather arbitrarily therefore, it appears reasonable to adopt uncertainties of $\pm$ 20 miles, equivalent to $\pm 0.3°$ in latitude and $\pm 1.2°$ in longitude, for the 1950.0 epochal position.

In 1945 a large amount of compass data was obtained from the flights of the British Lancaster "Aries" (Maclure 1946) on tracks near Amundsen's pole position, and on a flight from Whitehorse, Y.T. to Shawbury, England. The position of the dip pole estimated from the data was near 74°N., 100°W. In view of the serious deviation troubles inherent in the use of compasses in a region of greatly reduced horizontal intensity, and the distance of the flight paths from the true position of the dip pole, this comparatively accurate determination represents a remarkable achievement. It also suggests that crustal anomalies cannot be very large around Boothia Peninsula and Prince of Wales Island.

Pole determinations after 1950

In 1953 the recently completed three-component airborne magnetometer of the Dominion Observatory (Serson, Mack, and Whitham 1957) was test flown over all the provinces of Canada in an R.C.A.F North Star. Two of the flights passed close to the estimated position of the dip pole: one of these was northward along the western side of Prince of Wales Island, turning easterly along Barrow Strait to Cornwallis Island and the second was westerly from Resolute to Viscount Melville Sound with a turn to the south near the mouth of M'Clintock Channel. The main purpose of these flights was to test

the operation of the equipment under all field and flight conditions that could reasonably be expected in Canada; the determination of the dip pole position was a secondary aspect of the flight program. The magnetic declinations measured along 75 miles of flight-lines within a distance of 50 miles from the dip poles were corrected, so far as possible, for the effects of aircraft magnetism. The estimated centre of the area of convergence of the linearly extrapolated magnetic meridians was 74.4°N., 98.1°W. Unfortunately, errors in position and uncertainties in the corrections for aircraft magnetism and its changes are such (Serson and Whitham 1958) that the position of the dip pole determined in this way is uncertain by at least ±0.2° in latitude and ±1.6° in longitude. Three points, however, should be emphasized. Although only declination information was used to locate the dip pole, the instrument is not a compass and is not affected in the same way by reduction of the directive force near the pole. Secondly, the small area of convergence obtained again suggests that local anomalies in this region are not large. It would therefore appear to be quite reasonable to predict the approximate position of the dip pole by the convergence of magnetic meridians provided the stations used are less than about 100 miles from the dip pole. (see also Steen, Russeltvedt, and Wasserfall 1933). This is entirely different from assuming that the compass needle points toward the magnetic pole at all latitudes. Thirdly, the dip pole position given above is not corrected for magnetic disturbances, since such corrections, under the conditions existing at the time, are equivalent to less than the estimated uncertainty in the position as quoted above.

In 1955 the United States Naval Ordnance Laboratory vector airborne magnetometer was flown in the neighbourhood of the dip pole. The final results of these flights are not known to the authors, but preliminary estimates communicated privately by Stockwell in 1956 placed the dip pole in Viscount Melville Sound, north of Prince of Wales Island.

Whitham and Loomer (1956) have described the diurnal and annual motions of the north magnetic dip pole produced by disturbance variations of external origin, using the data then available from the magnetic observatory at Resolute. They also concluded that in 1955 the secular variation field of internal origin was producing a secular drift in the position of the dip pole of about 4 miles per year slightly east of north. Their general conclusions regarding the magnitude and nature of the dip pole motion produced by ionospheric and extra-terrestrial currents remain unchanged. Thus the daily track of the dip pole at a time of moderate magnetic disturbance approximates an ellipse with a long axis of *ca.* 30 miles running roughly north-south and a short axis of *ca.* 18 miles east-west. During a severe disturbance the effective position of the dip pole can easily shift some 50 to 100 miles.

The additional data now available consist of an extended series of continuous three-component magnetic records from the magnetic observatory at Resolute (50 months as compared with 20 months available in 1956), and a new series of isomagnetic charts for Canada for epoch 1955.0, prepared on

a scale of 100 miles to the inch by Madill and Dawson (1956) and Dawson (1956). These writers compiled the latter charts independently of Hutchison's earlier work, although they used the same basic data and in addition data from northern observatories, data obtained by Loomer during the cruise of the *Labrador* through the northwest passage in 1954, and by Serson and Whitham during arctic flights in 1953 and 1954. The data now provide a good basis for estimating the present secular drift of the dip pole, and hence, if we know the position for one epoch, for estimating that for a later one. For the reasons outlined earlier it seems reasonable to adopt the position 74° ± 0.3°N., 100° ±1.2°W. at 1950.0 as the base position for a calculation of this kind.

The present secular motion of the north magnetic dip pole

Because of the proximity of the Resolute magnetic observatory to the dip pole, the secular variation of the earth's magnetic field at the two locations must be very nearly identical, if it is assumed that the secular change has its origin inside the core of the earth. Since November 1953, continuous measurements of the magnitude and direction of the earth's magnetic field have been made at Resolute. Fig. 1 shows a plot of the mean annual values of the geographic north (X) and geographic east (Y) components of the horizontal magnetic field for the years 1954 to 1957 inclusive. In addition, two points prior to 1954 are plotted in the X-plot. These were computed from single component (declination) records obtained during 1952 and 1953, suitably corrected for the effect of changing inclination in a small ambient field. In the Y-plot, the three points shown prior to 1954 were estimated from older scattered absolute values after making approximate corrections for disturbance so far as is now possible. Least-square calculations assuming a constant secular change during this time give the slopes of the best straight lines fitting the data from 1954 to 1957 inclusive. These values were $\dot{X} = +25$ gammas per year and $\dot{Y} = +4$ gammas per year (1 gamma $= 10^{-5}$ oersted). The declination results show that the rate of change of X must have been constant for some years prior to 1954, and the additional Y data, although known to be of only secondary accuracy for this purpose, strongly suggest that the rate of change of Y previous to 1954 cannot have been very different from 4 gammas per year. For example, if quadratic or cubic expressions in time are fitted to the Y data from 1954 to 1957, the extrapolated value of Y around 1950 is numerically very much larger than our estimate from corrected old field observations. We conclude that although the rate of increase of Y is apparently decreasing, the results at present available suggest that a mean rate of 4 gammas per year in the last decade is the most reasonable estimate.

Assuming the approximate longitude of the dip pole to be 100°W., the rate of change of U and V can be calculated from $\dot{X}$ and $\dot{Y}$. (Appendix). Hutchisons's unpublished charts show the regional field gradients at the dip pole in the U and V components to be 8 gammas per mile and 4 gammas per mile, respectively. Therefore, if the secular change is regarded as being

produced by the drift of the regional field, without there being any appreciable change in form near the dip pole, the secular motion of the dip pole is 5(.6) miles per year to the north and 1(.1) miles per year to the east. This estimate is about 20 per cent greater than the earlier estimate of Whitham and Loomer (1956), which was based on much less data. The assumption made regarding comparatively minor changes in the form of the regional field near the dip pole over a half-decade or so is confirmed by the results of a similar method using the regional field gradients shown on the X, Y isomagnetic charts of Dawson (1956) for epoch 1955.0. The X, Y contours, in contrast to the U, V ones, show marked curvature in polar regions, making the determination of the relevant field gradients more uncertain. However, a similar process leads to a secular motion of 5(.5) miles per year to the north and 0.(.4) miles per year to the east. The close agreement in magnitude and direction between the secular drift values obtained by using the two sets of charts confirms the essential correctness of the assumption. This might also be expected because the change in magnitude of the axial dipole of the earth has a very small effect on the horizontal component of force at high latitudes.

A third estimate of the secular motion can be made by using potential theory and essentially the same data, although with different approximations. The lines of equal horizontal intensity display a considerably elongated pattern in the Arctic (Madill and Dawson 1956). If the eccentricity of this pattern is uniform for all isomagnetic contours of low intensity, the pole will be at the centre of the elliptical contours. In fact, however, the position of the dip pole is far south of the centre of the pattern and this has led to the suggestion that in reality there may be two poles, with a counterpart to the north magnetic dip pole that we have been discussing situated in the remotest part of the Arctic Basin. Recent Soviet observations and studies (Anon. 1954), however, apparently discredit the existence of such a second pole. Consequently, it seems worth while to neglect the fact that the dip pole is not at the centre of symmetrical elliptical H-contours. It is then possible to write the equation of the lines of equal potential in elliptical form. If the axes Ox′, Oy′ are taken to coincide with the principal axes of the ellipse of lowest intensity that can be determined (H = 1000 gammas), and if the origin is taken to be at the dip pole, the potential V at (x′, y′) can be written

$$V = V_\circ + \frac{a}{2}x'^2 + \frac{b}{2}y'^2.$$

$$\text{Therefore, } X' = -\frac{\partial V}{\partial x'} = -ax'$$

$$Y' = -\frac{\partial V}{\partial y'} = -by'$$

$$\text{and since } H^2 = X'^2 + Y'^2$$

$H^2 = a^2x'^2 + b^2y'^2$ is the equation of the isomagnetic lines in H. The velocity of the pole parallel to Ox′ is $v_{x'} = \dot{X}'/a$ and parallel to Oy′ it is $v_{y'} = \dot{Y}'/b$. Using the best determination by Dawson, revised to epoch 1960.0, of the contour for H = 1000 gammas, which is shown in Fig. 2, then Ox′ is rotated about 13° west of geographic north and a = 6 gammas per mile, b = 9 gammas

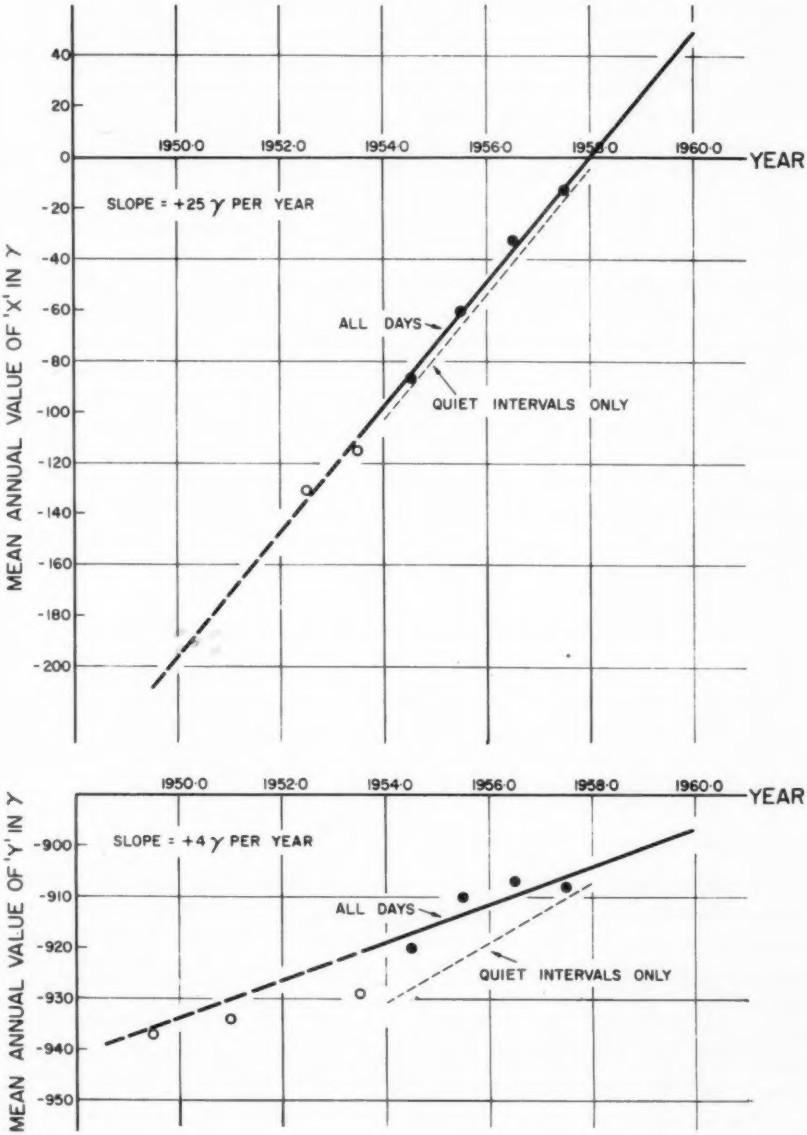


Fig. 1. The mean annual values of the geographical components of the horizontal magnetic field intensity at the magnetic observatory at Resolute for the years 1954 to 1958.

per mile. After calculating $\dot{X}'$, $\dot{Y}'$ from $\dot{X}$, $\dot{Y}$, estimating $v_{x'}$, $v_{y'}$ and resolving back to geographical co-ordinates, the secular motion can be estimated to be 3(.9) miles per year to the north and 0(.2) miles per year to the east. Considering the approximation involved, these results are in substantial agreement with those given above, the mean of which indicates a secular drift of 5.5 miles per year to the north and 0(.7) miles per year to the east.

We conclude therefore that the magnitude and direction of the present secular drift are comparatively accurately known. One source of systematic error is that in taking mean annual values at high latitudes, the effect of ionospheric and extra-ionospheric sources may not be truly zero. There is in fact good evidence that this is so, and in Fig. 1 the dotted lines show the least-square slopes obtained by fitting the mean annual values of the magnetically quiet intervals only. These slopes should be substantially free of any such effect since at quiet times, by definition, disturbances are at a minimum. The selection of quiet intervals was made using the tables prepared by the International Association of Geomagnetism and Aeronomy, and by inspection. The least-square slopes obtained were $X = +25$ gammas per year and $Y = +6$ gammas per year. If these estimates are used in the above calculations, the secular drift is unchanged in magnitude but is very slightly more easterly. The displacement of the two sets of lines in Fig. 1 shows that the averaged effect of disturbance is not quite zero but is a vector of a few gammas directed approximately northeast (to the geomagnetic pole mentioned later)[1].

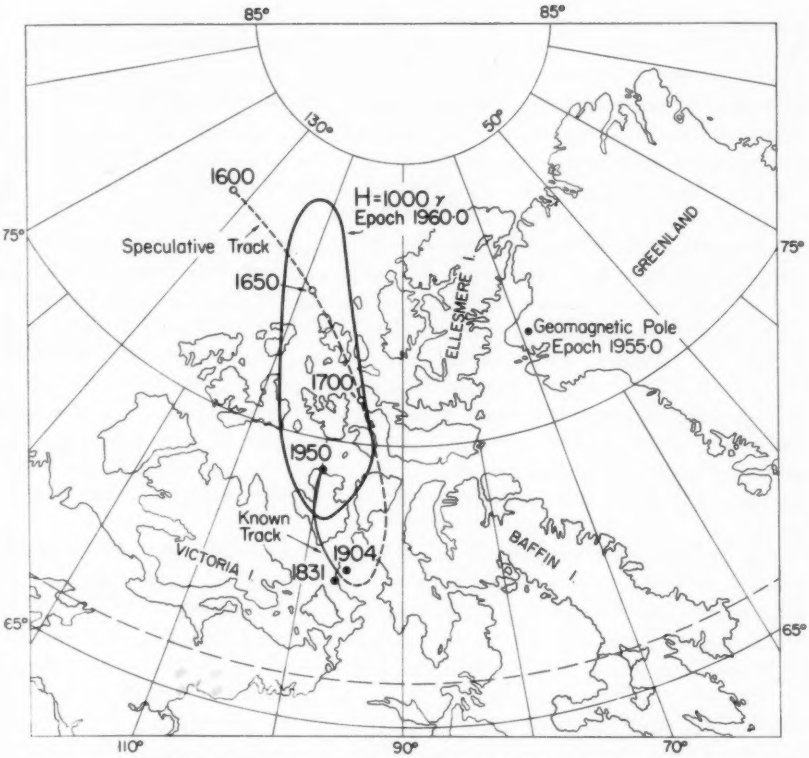
The estimated position of the dip pole, epoch 1960.0

The predicted movement in this decade is 0.8° in latitude and 0.4° in longitude. Assuming Hutchison's 1950.0 position, the predicted position for epoch 1960.0 becomes 74.8° ±0.3°N., 99.6° ±1.2°W. We are more confident of its present secular motion than its present absolute position, particularly in longitude. This is illustrated in Fig. 3.

The geophysical significance of the dip pole and its motion

Quite naturally much scientific interest is attached to the motion of the north magnetic dip pole (Madill 1948; Beals, *et al.* 1954). The revised estimates outlined above are in good agreement with those made by Whitham and Loomer (1956), and the earlier conclusion that the present northerly drift substantially agrees with the mean northerly motion for the last half-century is confirmed. The present very small easterly motion is obviously much more uncertain, and the distribution of mean annual values shown in Fig. 1 suggests it may be decreasing. In any case, because the position of the

[1] *Note added in proof.* Since the completion of this paper we have received information from Rear Admiral Charles Pierce (private communication) that the U.S. Coast and Geodetic Survey have computed the 1960 position of the north magnetic dip pole as 74.9°N., 101.8°W. It has been suggested that a compromise position 74.9°N., 101°W. be adopted for use on Canadian and world charts. Although this position will be to the west of the 1950 position, we are confident that the secular motion of the dip pole is slightly east of north.



o...Estimated positions of the North Magnetic Pole (after van Bemmelen).

•...Observed positions of the North Magnetic Pole:

1831 - Ross
1904 - Amundsen
1950 - Hutchison ≡ 1945 Aries

Fig. 2. The speculative and known tracks of the north magnetic dip pole and the position of the contours for H = 1000 gammas at epoch 1960.0.

pole depends entirely on the magnitude of the higher harmonic terms in a spherical harmonic expansion of the main field, its motion is apparently not related in any simple way to the broad-scale core motions deduced by an analysis of the eccentric dipole at different epochs (Vestine 1953). We now know this result is true of the geomagnetic field as a whole in Canada (Whitham 1958). It should, of course, be clear that the secular motion of the pole is a consequence of secular variation and not its cause. Consequently, this motion can provide a simple picture of the secular variation in a region very close to the pole only.

It has been suggested that the secular motion is really a linear oscillation in which constraints imposed by a fixed magnetic anomaly (the great arctic

anomaly) impose essentially linear trapping on what is thought to be fundamentally a westward circular motion around the geographic pole (Hope 1957a and 1957b). Much of the evidence for this rests on the reconstructed pole positions of van Bemmelen, which are shown in Fig. 2. These however are known to be unreliable since they depend on magnetic information from low latitudes only. When magnetic data from low latitudes only are available, the position of the dip pole can best be estimated by using the techniques of spherical harmonic analysis. With a finite number of terms in the expansion used (customarily 48 terms) the pole positions deduced in this way are in error by 100 miles or more, even today with our vastly increased knowledge of the distribution of the intensity of the magnetic field. Simpler methods, such as assuming dipoles or extrapolating isogons or both, lead to enormous errors. In addition, the authors consider that the elongated horizontal intensity contours can be explained by non-dipole sources inside the core, and they know of no evidence that convincingly associates the so-called "anomaly" with the geology of the area. This, however, is not denying the existence of crustal anomalies. Indeed, it would be surprising if they did not exist, and they can easily cause errors in the determination of the position of the pole.

In our opinion, therefore, the future motion of the pole cannot be reliably predicted at this stage because we cannot predict the secular variation of the earth's field. Our knowledge of the life times of isoporic foci (centres of rapid annual change of the magnetic field) does suggest that the present northward motion is likely to persist within a factor of two in magnitude for the order of 100 years. Even this cautious prediction is really only an intelligent guess. The significance and persistence of the eastward motion is more difficult to assess. Whitham (1958) has commented on the lack of evidence in Canadian data for the generally accepted westward-drift of the non-dipole component of the earth's field, and has shown that there is no evidence for a 480-year rotation period. Studies of rock magnetism have suggested that, among other phenomena, repeated reversals of the polarity of the earth's main magnetic field have occurred. The average position of the magnetic dip pole during a time of *ca.* 100,000 years might be expected to be that of the geographic north pole, because of the dominant influence of the Coriolis force on core motions, and reversals apparently occur about once every 10,000 years. This corresponds to a rate of change of magnetic latitude at only one fourth of the present rate, which can therefore not be considered as unusual.

The significance of the dip pole and of the elongated shape of the isomagnetic contours in studies of magnetic disturbance is still obscure. Most synoptic studies show that the axis of the dipole at the earth's centre, which best represents the earth's magnetic field and can be thought of as intersecting the surface of the earth at the so-called geomagnetic poles, is of more importance in the study of aeronomy. The northern geomagnetic pole is only very slowly changing position and its latest determined position was 78.3°N, 69°W at epoch 1955.0 (Finch and Leaton 1957), some 600 miles northeast of the magnetic dip pole. However, many of the details concerning

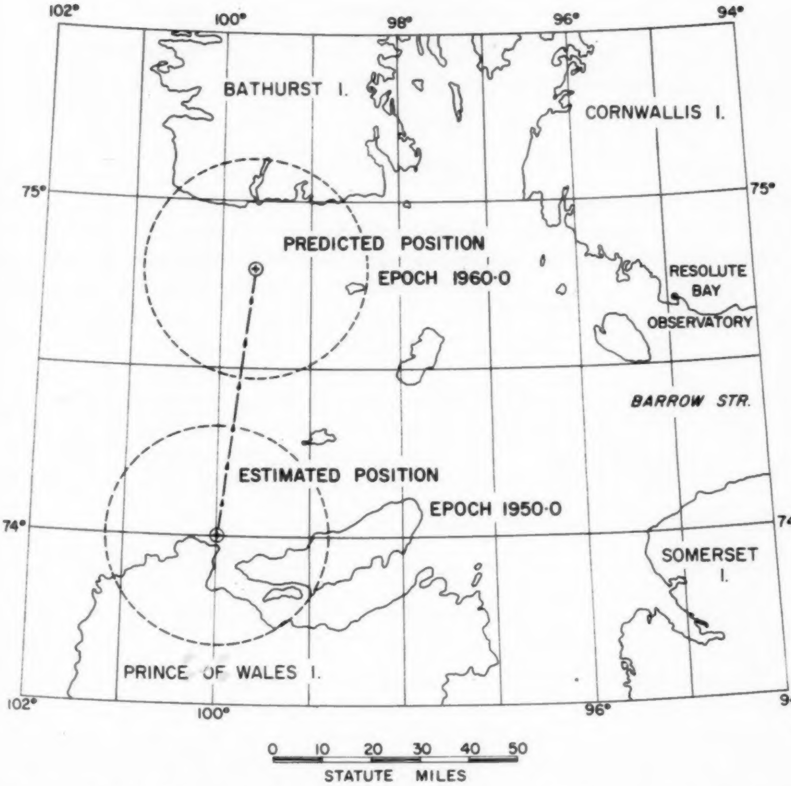


Fig. 3. The predicted dip pole position, epoch 1960.0, and the present secular motion of the dip pole. The circles indicate the estimated uncertainty of the true epochal positions.

the possible penetration of charged particles into the ionosphere along magnetic lines of force, and the interaction of the magnetic field with streams of charged particles from the sun may be partially explained by the deviation of the earth's field from that of a dipole. The position and motion of the dip pole are convenient indicators of this deviation from a dipole field.

The zero isopor of declination

This passes through the dip pole in the direction of the change of horizontal field intensity. Consequently its direction at the pole should be in the direction of the pole motion. There is a small discrepancy between the direction shown in the isogonic chart for Canada, epoch 1955.0 (Madill and Dawson 1956), and the direction of motion deduced in this paper and by Whitham and Loomer (1956). This will be corrected in the next isogonic chart for epoch 1960.0, which is in preparation.

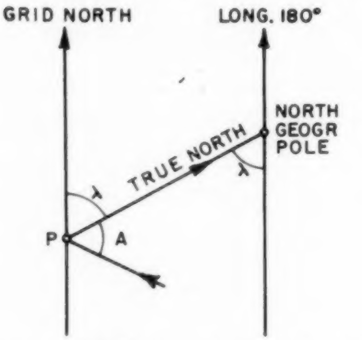
Acknowledgements

We wish to thank Mr. R. G. Madill and Dr. C. S. Beals for their encouragement, and for suggestions during the preparation of this manuscript.

Appendix

Greenwich grid system

On a polar stereographic projection, one draws straight lines parallel to a fixed meridian, in this case the meridian of Greenwich. Just one line passes through any place P on the map. The direction of this line through P (strictly the direction parallel to the direction of the true north on the Greenwich meridian) is called grid north. A grid bearing is obtained from the corresponding true bearing by adding (if west) or subtracting (if east) the longitude of P.



True bearing $= A$
Longitude $= \lambda$
Grid bearing $G = A \pm \lambda$

where λ is positive for west longitude and negative for east longitude.

The advantage of this system is that the north geographic pole is no longer a singular point. In simplifying the problem of polar direction, the grid system also simplifies the pattern of isogonic lines for magnetic declination. There is no longer a singularity at the north geographic pole; the isogonic lines radiate from the north magnetic dip pole only.

For purposes of analysis, the earth's total magnetic vector $\bar{F}$ is usually resolved into three orthogonal components X (true north component), Y (true east component) and Z (vertical component). X and Y are generally computed from the measured values of D (magnetic declination) and H (the horizontal component of $\bar{F}$)

$$X = H \cos D \tag{2}$$
$$Y = H \sin D \tag{3}$$

This leads to geometrical complications in X and Y at the north geographic pole, but these complications can be eliminated by using the grid reference system. In this system we define the following terms

grid variation (grivation) $G = D - \lambda$ (4)

where λ is the east longitude,
D is positive for east declination
and negative for west declination

U (grid-north component) $= H \cos G$ (5)

V (grid-east component) $= H \sin G$ (6)

From equations (2) (3) (4) (5) (6), the relationship between U, V, X, Y, can be expressed as follows

$$\begin{aligned} U &= H \cos (D - \lambda) \\ &= X \cos \lambda + Y \sin \end{aligned} \tag{7}$$

$$\begin{aligned} V &= H \sin (D - \lambda) \\ &= -X \sin \lambda + Y \cos \lambda \end{aligned} \tag{8}$$

From (7) (8), the rate of change of U and V is

$$dU/dt = \dot{U} = \dot{X} \cos \lambda + Y \sin \lambda \tag{9}$$

$$dV/dt = \dot{V} = -\dot{X} \sin \lambda + Y \cos \lambda \tag{10}$$

For a more complete description of the Greenwich grid system see references (Maclure 1946) and (Hutchison 1949).

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FREEZE-THAW FREQUENCIES AND MECHANICAL WEATHERING IN CANADA*

J. Keith Fraser†

THE repeated freezing and thawing of water in rock crevices and soil material is recognized as an important factor in mechanical weathering. The comparative importance of the process in northern and southern Canada has been examined in this preliminary study, which is not concerned with weathering under alpine conditions, and only indirectly with the role of freezing and thawing in the creation of patterned ground. Mechanical weathering is defined as the disintegration of rock in place, as opposed to chemical decomposition or to erosion, which requires a transporting agent. The freeze-thaw frequency at a particular station is the annual number of times the recorded temperature falls below the point of effective freeze following a period when the temperature was at or above the point of effective thaw.

Scattered through the descriptive literature pertaining to arctic and subarctic regions are references (Tarr 1897, Eakin 1916, Jenness 1952, Bird 1955) to the widespread occurrence of frost-riven rock materials, rock deserts *(felsenmeere)*, talus concentrations and comminuted erratics. This obvious and widespread mechanical weathering is attributed to frost action, either by extreme cold, by repeated freezing and thawing, or by both, leaving the impression that such predominant rock disintegration is characteristic of high latitudes simply because low temperatures and repeated freezes occur there. There appears to have been little effort to compare the frequency of freezes and thaws in high with that in middle latitudes. Although some observers have noted that freezing and thawing is less frequent in high than in middle latitudes, these observations were of short term nature and more concerned with soil structures than with rock weathering (Högbom 1914, Elton 1927, Black 1954). Accordingly, it seems worth while to examine the importance of freezing and thawing by investigating the frequency of freeze-thaw cycles by the use of Canadian meteorological records.

It has been shown (Reiche 1950, p. 10) that rocks do not effectively disintegrate due to climatic temperature changes only (quite apart from the effect of freezing water) either by the difference in volume change of the outside and the inside of the rock, or by the differential change in volume

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of the different component materials. The experiments involved in these studies were concerned mainly with the effect of a rise of temperature, as in hot deserts, but a drop of temperature would have as little effect. It may thus be assumed that extreme low temperatures by themselves are of little importance in rock weathering.

The disruption of rocks by the freezing of water contained in joints, cracks or bedding planes is recognized as an important process in landform destruction. Water experiences a 9.05 per cent volume increase on freezing and exerts tremendous pressure when freezing in a confined space. This force is at its maximum only under certain conditions. "This is because the water in most rocks forms a system open to the atmosphere, or is in communication downward with a zone of saturation which remains unfrozen, or includes air pockets (i.e. fails completely to saturate the material). In these cases, fluid expulsion commensurate with the expansion of freezing may occur, or the volume increase may be taken up by compression of air . . . Nevertheless, water-filled cracks or joints which terminate downward and which are narrow and perhaps irregular may be converted into essentially closed systems by preliminary freezing of the water in their superficial parts. In such cases the combination of expansion and low compressibility may exert a disruptive force which, if the temperature continued to fall and rock pressure permitted, would approach 30,000 pounds to the square inch at —22°C." (Reiche 1950, p. 12). As Grawe points out, this temperature (—7.6°F.) is not excessively low or uncommon in temperate climates (Grawe 1936, p. 179).

Previous studies

The work of Russell (1943, Visher 1954) is probably the most thorough of the few studies of the distribution of freeze-thaw frequencies. It concerns only the continental United States and is based on the records of the daily maximum and minimum temperature at 863 stations over 18 years. Russell's map shows a zone of highest freeze-thaw frequency in the Rocky Mountains in Colorado and Wyoming, from which frequencies decrease outward in all directions; a belt of comparatively high frequencies extends northeastward to the Great Lakes. In the central United States, where temperatures are affected less by altitude than by latitude, frequencies decrease southward, and there is also an indication of a decrease northward in Minnesota. If Russell's methods were extended into central Canada, the frequencies would likely decrease northward in a manner somewhat similar to their decrease in the southern states.

Visher (1945, 1954) included in a series of climatic maps of the United States two maps of freeze-thaw frequencies. The first map (Visher 1945, p. 730, Fig. 23) shows the average number of days per year when the temperature fluctuated between freezing and thawing, and was based on the difference between the annual number of nights with frost and the number of days with temperatures continually below freezing. This map shows an increase

northward from the Gulf of Mexico to the southern part of the Great Lakes and the beginning of a decrease into Canada. The second map (Visher 1945, p. 731, Fig. 24) shows potential freeze-thaw frequencies as indicated by the number of days per year when the daily mean temperature was between 20°F. and 50°F., thus assuming that with a normal daily range of 25°F. (the average for the United States) the daily maxima or minima could rise or fall to 32°F. This map also indicates an increase northward from the Gulf of Mexico and a corresponding decrease near the Great Lakes. As will be shown, Visher's use of the mean daily range of 25°F. is inapplicable to arctic stations.

Peltier worked out a theoretical relationship between climatic factors and mechanical weathering as represented by frost action (Peltier 1950, p. 219, Fig. 2). He plotted mean annual temperature against mean annual rainfall to illustrate the regional importance of mechanical weathering. His zone of "strong" frost action occupies the space on his graph between the mean annual temperatures of 0°F. and 23°F. and between the mean annual rainfalls of 10 inches and 50 inches. In applying Peltier's zone of maximum frost action to a map of Canada, these temperature limits confine it to an area extending roughly from the southern coasts of the Queen Elizabeth Islands to a line from James Bay to Great Slave Lake. The zone is further restricted by rainfall limits (total precipitation used here) to Canada south of the 10-inch isohyet, which runs from Chesterfield Inlet west to Great Slave Lake and thence northwest along the Mackenzie River. Peltier's zone of maximum frost action therefore does not agree with the maps of Russell and Visher, or with the findings of the present study.

Limitations of the present study

Before examining the meteorological records and counting the freeze-thaw cycles, it is necessary to decide what to consider as the limits of effective freeze and thaw. Russell considered that a drop in temperature to 28°F. or less in the instrument shelter should indicate an effective freeze at ground surface. A thaw was counted at 32°F. or more, as Russell reasoned that air temperatures may lag behind ground temperatures, and that, when an instrument 5 feet above the ground recorded 32°F., it was likely that the ground temperature was higher. The cooling effect of permanently frozen subsoil and rock in northern regions may partly cancel this disparity and in such regions an effective thaw may not take place until the temperature rises a few degrees above 32°F. A range of 10 degrees, from 25°F. to 35°F., was used by D. W. Boyd (personal communication) in some unpublished work on Canadian stations. For the purpose of the present study it was decided that a freeze-thaw cycle is represented by a rise to 34°F. following a drop to 28°F. By using Russell's four-degree range a somewhat higher, by using Boyd's ten-degree range a somewhat lower number would have been obtained (Table 1).

Table 1. Number of cycles at three stations based on different temperature ranges.

Station	*Latitude*	*Number of cycles recorded in 1949*		
		4°F. range (32° — 28°)	*6°F. range* (34° — 28°)	*10°F. range* (35° — 25°)
Eureka	80°00′N.	15	9	5
Port Radium	66°05′	39	29	18
Regina	50°27′	83	74	54

In this study an attempt is made to stress the importance of the latitudinal influence in determining the frequency of freeze-thaw cycles and to disregard the influence of altitude. Of the 42 stations examined 29 are located below 900 feet above sea-level, 8 between 900 feet and 1,600 feet above sea-level, and 5 between 1,600 feet and 3,000 feet above sea-level (Table 2). Russell points out that in general freeze-thaw frequencies increase at higher altitudes, there being cycles in all months of the year in

Table 2. Average annual freeze-thaw frequencies at 42 Canadian stations.

Station	*Latitude*	*Average annual freeze-thaw frequency*	*Altitude (feet)*
Alert, N.W.T.	82°30′N.	22	205
Eureka, N.W.T.	80°00′	12	8
Isachsen, N.W.T.	76°47′	14	83
Mould Bay, N.W.T.	76°16′	12	50
Resolute, N.W.T.	74°43′	13	56
Holman Island, N.W.T.	70°30′	21	30
Cambridge Bay, N.W.T.	69°07′	16	45
Aklavik, N.W.T.	68°14′	25	30
Coppermine, N.W.T.	67°47′	21	13
Port Radium, N.W.T.	66°05′	28	600
Norman Wells, N.W.T.	65°18′	32	240
Baker Lake, N.W.T.	64°18′	29	30
Frobisher, N.W.T.	63°44′	25	68
Reliance, N.W.T.	62°43′	34	539
Yellowknife, N.W.T.	62°28′	27	682
Ennadai, N.W.T.	61°08′	26	1,065
Fort Smith, N.W.T.	60°01′	48	665
Churchill, Man.	58°45′	28	115
Port Harrison, Que.	58°27′	33	66
Fort Chimo, Que.	58°06′	42	117
Brochet, Man.	57°53′	43	1,180
McMurray, Alta.	56°39′	64	1,216
Knob Lake, Que.	54°49′	53	1,550
The Pas, Man.	53°58′	39	894
Trout Lake, Ont.	53°50′	40	720
Edmonton, Alta.	53°34′	59	2,219
Prince Albert, Sask.	53°15′	56	1,414
Biggar, Sask.	52°03′	65	2,154
Moosonee, Ont.	51°16′	49	34
Regina, Sask.	50°27′	60	1,884
Winnipeg, Man.	49°54′	41	786
Dryden, Ont.	49°48′	54	1,220
Lethbridge, Alta.	49°38′	76	2,961
Estevan, Sask.	49°04′	54	1,884
Timmins, Ont.	48°30′	49	1,100
Arvida, Que.	48°26′	56	335
Fort William, Ont.	48°22′	66	644
Sault Ste. Marie, Ont.	46°32′	57	675
North Bay, Ont.	46°22′	52	1,210
Ottawa, Ont.	45°20′	54	339
Malton, Ont.	43°41′	60	578
Windsor, Ont.	42°17′	51	637

contrast to stations at lower altitudes where higher summer temperatures prevail.

Most of the station records examined cover a period of 5 years, but the comparatively recent establishment of stations in the Queen Elizabeth Islands and several incomplete records reduced some periods to only 3 or 4 years. The average annual frequency of freeze-thaw cycles was determined for each of the 42 stations (Table 2) by examining the daily recorded maximum and minimum temperatures (Anon. 1949-53).

It is recognized that the figures resulting from this study are unlikely to indicate the complete effect of frost action in arctic regions. The temperatures recorded are not ground temperatures, but air temperatures in instrument shelters 5 feet above ground. Most of the stations, especially in the north, are on sea or lake coasts or in river valleys. Freezes and thaws may well be more frequent even at short distances inland or upland from the stations. For instance, Churchill at the mouth of the Churchill River on Hudson Bay has a much lower freeze-thaw frequency than Brochet, 270 miles inland at about the same latitude (Table 2). Mathews's data (Fig. 6) in British Columbia show similar trends although there, of course, altitude affects the frequencies. Slopes facing south or southwest are likely to have melting well before the air temperature rises above 34°F. Dark-coloured rocks may absorb enough heat during the period of high sun in May and June to melt the water contained in their crevices, even when the thermometer still indicates a temperature below freezing point. In such instances even the clouding over of the sky may result in refreezing of this water. Grawe notes that there is less rock-shattering effect with slow freezing than with a sudden drop in temperature (Grawe 1936, p. 178). This disparity between recorded temperatures and actual ground temperatures may be offset as far as the number of freeze-thaw cycles is concerned by the probable lag of the melting of ice in deep rock crevices behind the seasonal rise of air temperatures.

Freeze-thaw frequency distribution

Examination of the temperature records shows conclusively that the average annual frequency of freeze-thaw cycles increases steadily from north to south in central Canada (Fig. 1). Despite the limitations just discussed, the difference between frequencies in the High Arctic and southern Canada is sufficiently great to make this observation valid.

In the five stations in the Queen Elizabeth Islands frequencies average 15 cycles per year. Alert, at the northern coast of Ellesmere Island, appears to be anomalous with 22 cycles, possibly the result of a foehn effect of the nearby mountains. Frequencies increase at stations on Victoria Island, along the arctic coast, and at Great Bear Lake near the Arctic Circle. They increase rapidly near the sixtieth parallel, Fort Smith and Fort McMurray having 48 and 64 cycles per year respectively. The rest of southern Canada has frequencies of over 40, with several stations averaging over 60

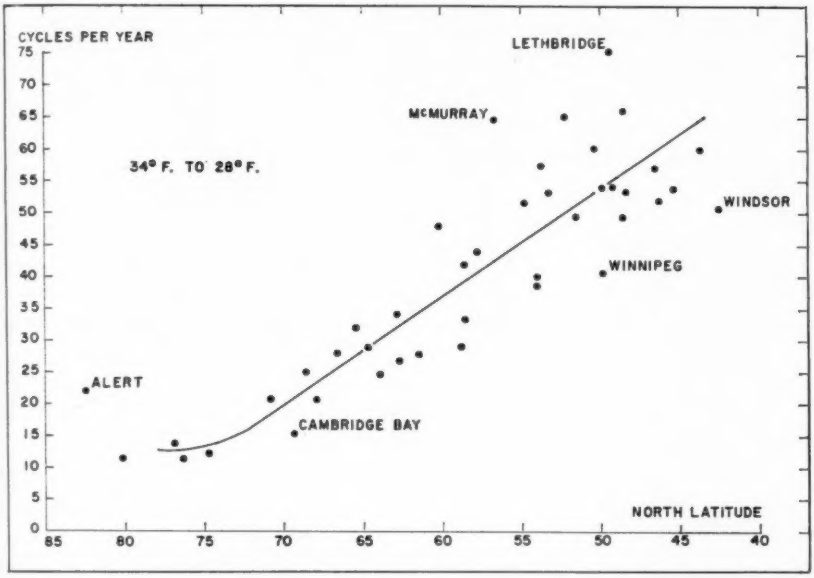


Fig. 1. Scattergram of average annual freeze-thaw frequencies plotted against latitude for 42 stations in Canada.

cycles per year, but a decrease appears near the international boundary. The effect of the Great Lakes may partly account for this reversal in east-central Canada and, as the maps of Russell and Visher show, there is another increase in frequency across the central United States before the trend is affected by the warmer southern areas.

The lines of equal annual freeze-thaw frequency in Canada according to the criteria used in this study are plotted on the map (Fig. 6). The data for western Canada are from W. H. Mathews, University of British Columbia (personal communication). The term *isopalimpex lines* is suggested for the isograms (Gr. *isos,* equal; *palim,* recurring; *pexis,* freezing).

Freeze-thaw frequency regimes

The freeze-thaw frequency regimes for a number of stations are shown in Fig. 2. As would be expected, most stations have a pronounced double maximum, occurring in the spring and in the fall when the daily mean temperature is passing the freezing point. The graphs of the far northern stations illustrate their short summer, which is indicated merely by a drop in frequency in July between their peak months of June and August. The long winter when no thawing occurs is shown by the 7 months during which no cycles are recorded. Toward the south the stations exhibit more summer

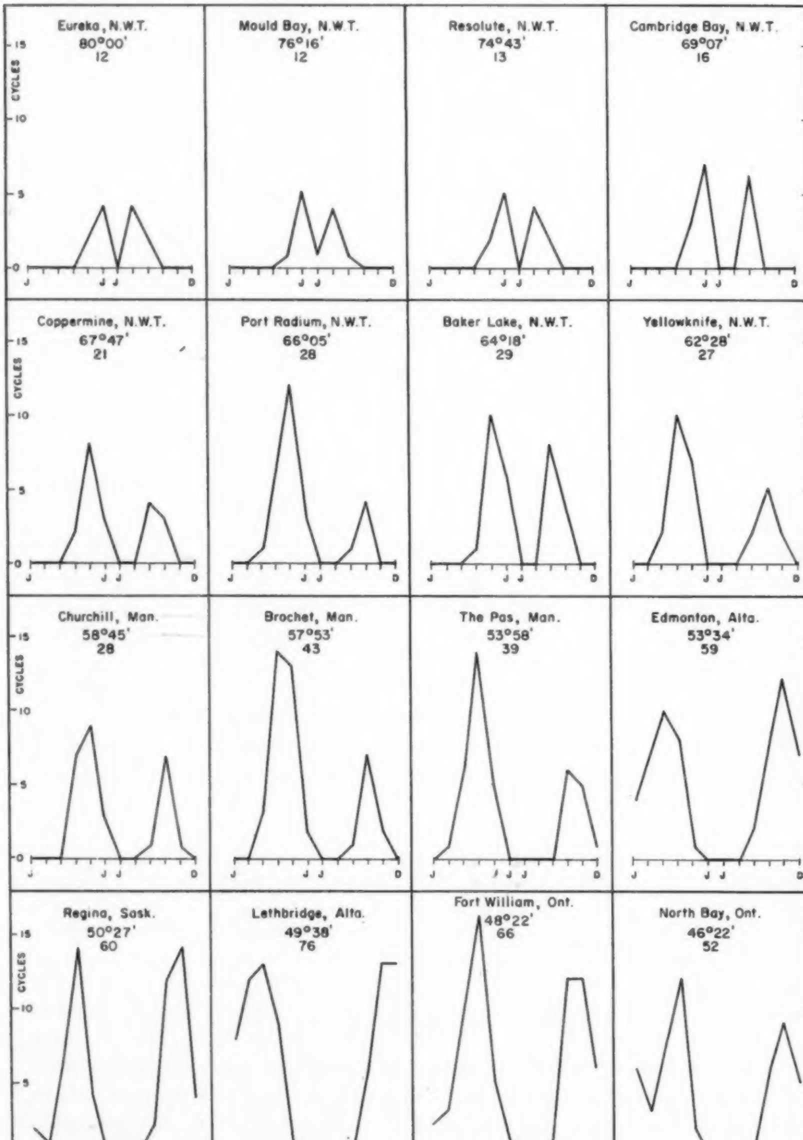
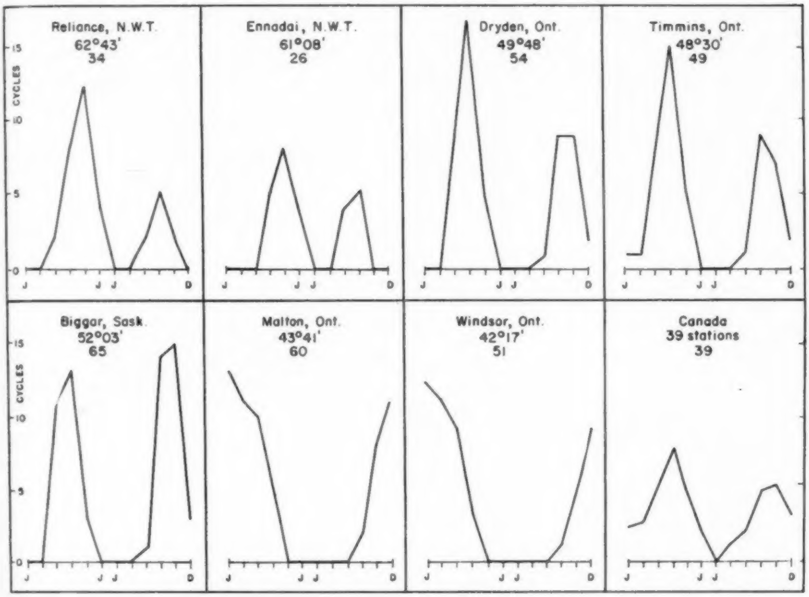


Fig. 2. Freeze-thaw frequency regimes of selected stations in Canada. (Continued on opposite page).



months without cycles, and the peaks spread farther apart and increase in amplitude. In southern Canada, represented by Malton (Toronto) and Windsor, the graphs become monocyclic with a single peak in January. At most stations cycles are more frequent in the spring than in the fall. The flurries of freeze-thaw cycles occur during the periods when the mean daily temperatures are passing the freezing point, which in the spring coincide with the periods of high sun and maximum insolation. The frequency depends on the daily amplitude of the air temperature and on the angle at which the trace of the mean temperature crosses the horizontal representing the freezing point. Greater insolation accompanying clear days in the spring results in greater daily amplitude, thus providing greater opportunity for cycles to occur. Less insolation in the fall results in a larger crossing angle and a smaller number of cycles.

The daily temperature trends for 1949 are shown in Figs. 3 and 4 for two stations, Regina, Saskatchewan, 50°27'N. and Eureka, Ellesmere Island, 80°00'N. These two stations show a remarkable contrast in their regimes. At Regina two cycles occurred in January and none in February. Four cycles occurred early in March and later in the same month the daily mean temperature passed the freezing point. Between March 23 and April 27 the day and night temperatures fluctuated across the freeze-thaw zone 24 times. Only three more freezes took place before rising summer temperatures became dominant. In the middle of September a marked flurry of fall cycles began, with sporadic freezes occurring in late September and early October. During a total of 55 days between October 8 and December

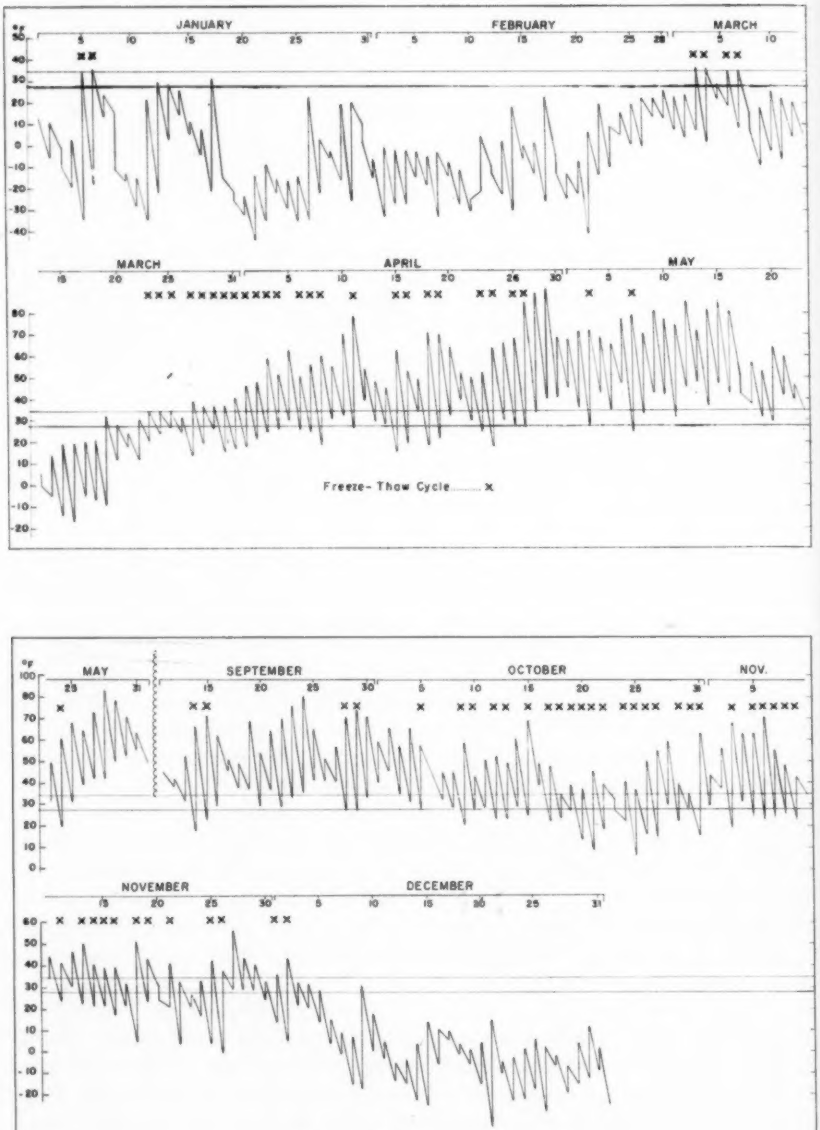


Fig. 3. Diurnal trend of temperature (°F.) for Regina, Sask. for January 1 to May 31 and September 11 to December 31, 1949. During the omitted summer period the temperature was consistently above the freeze-thaw range.

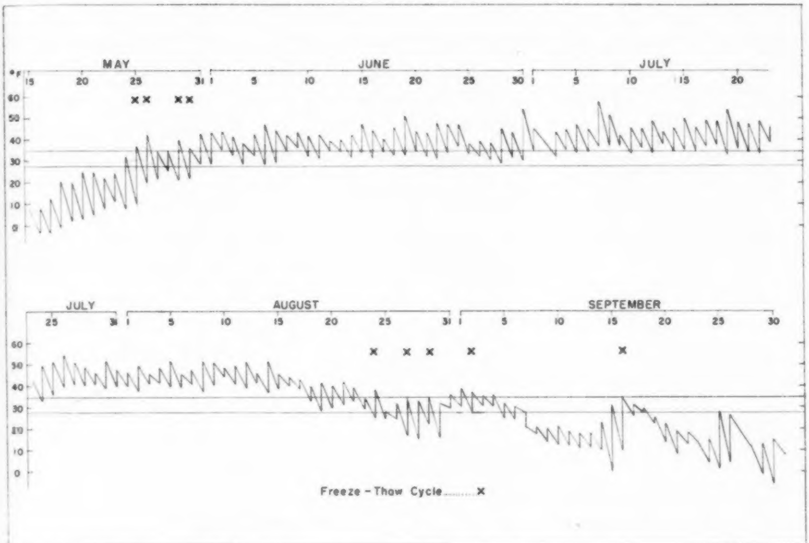


Fig. 4. Diurnal trend of temperature (°F.) for Eureka, N.W.T. for May 15 to September 30, 1949. The omitted winter period had temperatures consistently below the freeze-thaw range.

2 there were no less than 37 cycles, and after December 2 the temperature remained below the limit of effective thaw. The total number of cycles for Regina in 1949 amounted to 74.

During the same year Eureka experienced only 9 cycles, which occurred in two groups, 4 in late May and 5 in late August and early September. The temperature remained above 28°F. from May 31 to August 24, a period of 85 days, and it may be noted that it dropped to 32°F. or less, but not below 28°F., only 14 times during this period. These observations disagree with the statement of Jenness (1952, p. 246), referring to the arctic islands, that "alternate freezing and thawing takes place almost daily from May to October. . . ."

It is immediately evident from a comparison of the graphs that Regina has a much greater diurnal range than Eureka. According to the meteorological records the average difference between the mean annual maximum and minimum temperatures for Regina is 24°F. and for Eureka 12°F. Referring to Resolute in the Queen Elizabeth Islands, Cook (1955, p. 239) observes that "the amplitude of the daily variation changes with the season of the year, achieving maximum range in summer. However, summer diurnal variation is much less than in non-permafrost regions to the south. This is due to the greater uniformity of the mean surface air temperature, resulting from continuous daylight and the relatively weak circulation prevailing at this time of year." It is natural to expect that the greater the

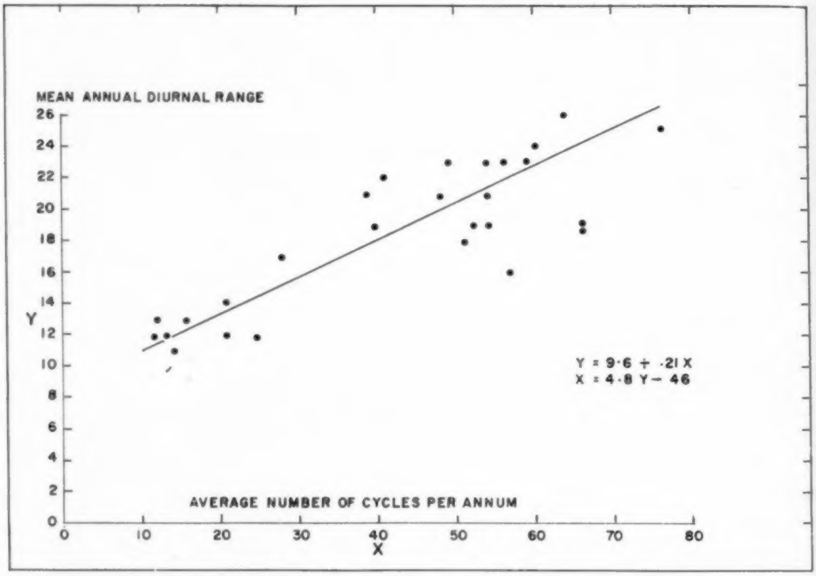


Fig. 5. Scattergram of average annual freeze-thaw frequencies plotted against average annual diurnal temperature (°F.) ranges for selected stations in Canada.

diurnal range, the more opportunity there would be for the night temperatures to fall below freezing and the day temperatures to rise above. Fig. 5 indicates some correlation between diurnal range and freeze-thaw frequency. A simple regression curve equation ($Y = 9.6 + 0.21X$ or $X = 4.8Y - 46$, where X equals the annual freeze-thaw frequency, and Y equals the mean annual diurnal range in degrees F.) allows a rough prediction of freeze-thaw frequencies from a knowledge of the diurnal range.

Availability of water

Peltier (1950, p. 218) states that there should be "a maximum zone of frost action located in the relatively humid subarctic regions". The high latitudes admittedly have a low annual precipitation, but this is partly offset by a low evaporation ratio and the holding of ground-water above the permafrost layer. In many places rock surfaces on slopes are kept continually moist throughout the summer by the melting of ice in the adjacent overburden. Precipitation records are invariably lower than the actual amounts. Meteorologists freely admit the difficulties of accurately measuring snowfall in the Arctic because of drifting; the occurrence of snow often coincides with winds. Furthermore, it is the author's experience that

there is considerably more precipitation in July and August than is recorded in the gauges. There is much fine rain that appears in the records as a trace only, yet may continue for 24 hours and be sufficient to drip from tent eaves and to moisten previously desiccated clay patches. Fog and dew are other significant sources of precipitation that are not included in the annual totals. The first few autumn snowfalls, recorded as snow, often melt rapidly, thus providing additional available water. The precipitation limit imposed by Peltier, therefore, has less significance than might be expected if the nature of the precipitation records and the above-mentioned additional sources of moisture are taken into account.

Conclusion

Whereas the concept of strongly predominant mechanical weathering in northern regions has been accepted, this paper has attempted to show that the fact that frost-riven rock is more evident in northern than in southern Canada is not the result of the lower temperatures or the freeze-thaw frequency, even taking into account the small number of stations examined, the brief periods of records, and the disparity between shelter recordings and ground temperatures.

A point that has not been discussed but that may be of prime importance in some arctic areas is that some *felsenmeere* may have been created under periglacial conditions. Climatic differences between periglacial periods and the present may well have included a more severe freeze-thaw regime, possibly approaching that of southern Canada today. Much of the shattered rock composing arctic landscapes undoubtedly is related to former conditions, although this point is seldom referred to by those who stress the importance of freezing and thawing in high latitudes.

It is suggested that the evident abundance of shattered rock derives from the absence of a concealing and insulating mantle of snow and vegetation in the north, and is therefore a *secondary* effect of the climatic factors of low precipitation and low mean annual temperatures. Mackay (1958, p. 46) points out that in northern Canada "weathering appears relatively more important, because of the lack of the thick vegetation mantle of the temperate areas. The role of mechanical weathering, especially the freeze-thaw cycle, may easily be overemphasized." Talus concentrations and *felsenmeere* are more visible to the observer, even in winter. Most of the light snowfall is blown by wind into gullies or into the lee of hills, in contrast to recorded depths of snow of 40 to 60 inches in southern Canada (Thomas 1953, p. 105), where more favourable temperatures and a greater precipitation combine with organic activity to promote the formation of a mantle of soil and vegetation, which helps both to conceal the results of frost action, and to insulate subsurface rock from low temperatures and from changes in temperature.

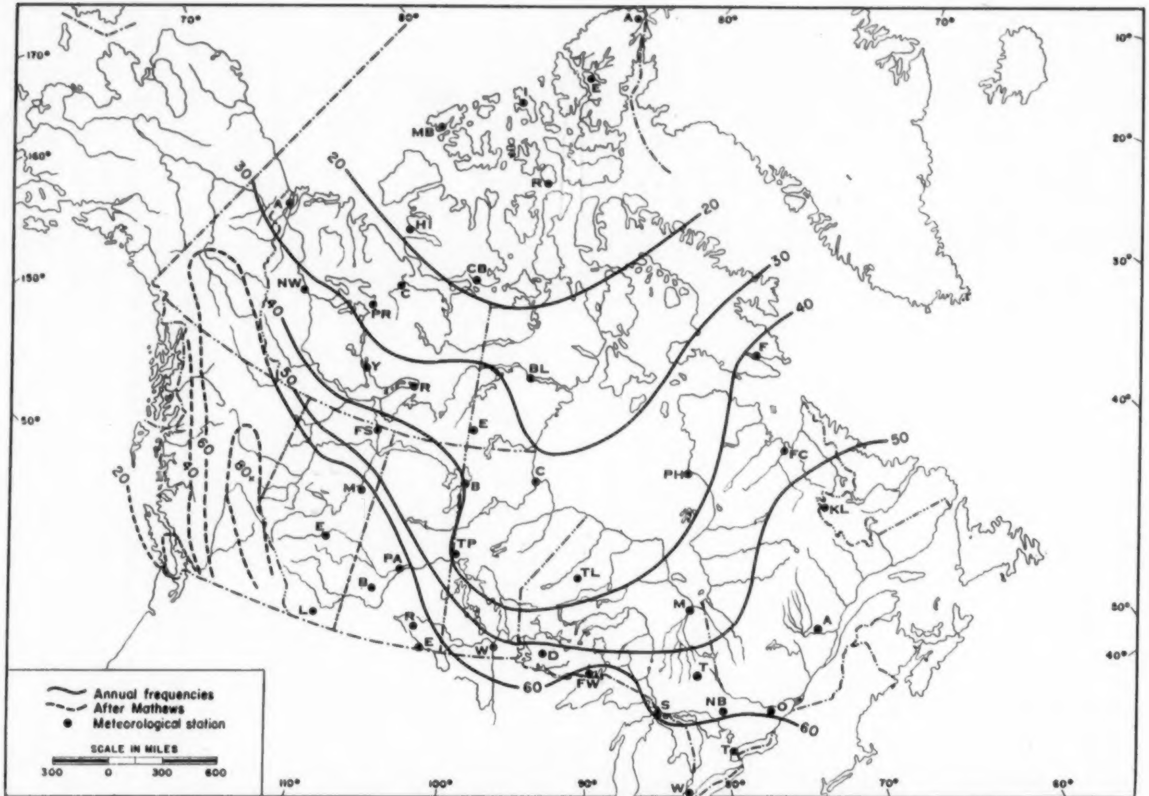


Fig. 6. Distribution of average annual freeze-thaw frequencies in Canada. The data for western Canada are from W. H. Mathews, University of British Columbia (personal communication).

It is hoped that this preliminary examination of freeze-thaw cycles in Canada will encourage quantitative studies on rock weathering as well as the accumulation of more widespread surface temperature recordings and the possible development of an air-surface temperature formula or correction factor applicable to northern latitudes.

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REVIEWS

THE INTERNATIONAL GEOPHYSICAL YEAR.

By WALTER SULLIVAN. *Published in: International Conciliation No. 521, January 1959, pp. 259-336. Carnegie Endowment for International Peace. 7¾ x 5½ inches. New York: Columbia University Press. 25¢.*

The purpose of *International Conciliation* is to present to its readers factual statements and analyses of problems in the field of international organization. Each issue is devoted to a single topic, and is written by a specialist in that field. It is published five times a year by the Carnegie Endowment for International Peace. The January (1959) issue is devoted, not to the *scientific* accomplishments of the IGY, but rather to the story of the IGY from the point of view of the historian.

The author, Walter Sullivan, was IGY reporter for *The New York Times,* which assigned him as a full-time reporter to the year. Mr. Sullivan visited many of the IGY Stations, among them the McCall Glacier Station in Alaska, run for the U.S. Program by the Arctic Institute. He knows the subject from the earliest inception, and has presented an account of the IGY from the forerunners of the year in the nineteenth century, through the Polar Years up to the preparation of the IGY. He explains the administration of the IGY, the basic policies, and the case of Chinese participation — the only exception to the general "triumph of science over politics". The publication ends with a chapter on "legacy of the IGY", where the author discusses some of the difficulties experienced in a meeting on common ground of so many countries. In spite of these difficulties, as an experiment in scientific co-operation across all political boundaries, the IGY was highly successful.

This publication will be most illuminating for the scientist who may only vaguely know the background of the IGY, and for those who realize that a knowledge of international relations is vital for their work.

SVENN ORVIG

SEALS, SEA LIONS, AND WALRUSES. A REVIEW OF THE PINNIPEDIA.

By VICTOR B. SCHEFFER. *Stanford: Stanford University Press, 1958. London: Oxford University Press. 9¼ x 6¼ inches, x + 179 pages, 32 plates, 15 text figures, 3 tables. $5.00.*

The last comprehensive review of the Pinnipedia appeared in 1880. The present work, by one of the world's foremost authorities on marine mammals, will doubtless be warmly welcomed by mamalogists everywhere. International interest in pinnipeds and their conservation has increased greatly in recent years, and there is a need, as pointed out by the author, for international agreement on names of the various groups and degrees of isolation of populations.

The book is compact, and although the binding could have been stronger, the publishers are to be congratulated on producing a work of this scope at a price that puts it well within reach of students and other interested persons.

The introduction is largely a tabulated summary of the numerical status of 55 known populations of pinnipeds in the world. The first five chapters of the book summarize up-to-date knowledge of the characteristics of pinnipeds (including reproduction, growth, and mortality), the evolution of the order and its families, the evolution of the genera, species, and subspecies, a description of the taxonomic procedure used by the author, and a systematic account by species and subspecies. The final chapter consists of a synoptic key to the genera. There is a

comprehensive list of world literature and a section of very good photographs of representative specimens of the various groups.

The work is authoritative and accurate, and contains material and references as recent as 1958. There is much controversy over some aspects of pinniped taxonomy. Many subspecies have been described on the basis of very scant material. Being a "lumper" like most non-taxonomists, I was glad to note a conservative approach to the problem by the author, who stresses the need for this, a uniform scale of values, and world-wide consistency.

Of interest to those concerned with the Arctic is the author's change of the genus name *Phoca* for three of the northern phocids to which it generally has been applied. The ringed seal becomes *Pusa hispida,* the harp seal becomes *Pagophilus groenlandica,* and the ribbon seal becomes *Histriophoca fasciata. Phoca* is retained only for the harbour seal *(P. vitulina).* Some scientists may not agree with the allocation of different generic rank to these four groups. However, there is at least partial support for this action from other workers, including those in the U.S.S.R.

Much new and intensive work is under way on the Pinnipedia, the results of which will quickly make some parts of this book obsolete. The author, by frequent use of question marks, has obviously attempted to stimulate further research, and it can be argued that now is the right time to do this when interest is at a peak, rather than to delay publication and wait for the results of recent and current work.

The work is not a hurried one. Dr. Scheffer has treated his subject with much common sense, and has done a great deal to place the controversial problems of pinniped taxonomy on a sound basis on which can be built better universal agreement.

H. D. Fisher

INSTITUTE NEWS

Gifts to the library

The Institute library acknowledges with thanks gifts of books and reprints from the following persons and organizations:

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Technical Papers of the Arctic Institute

No. 2 of this series, The Mammals of Banks Island. By T. H. Manning and A. H. Macpherson, 75 pages, maps, diagrams, tables, has appeared. Copies can be obtained from the Montreal Office at the price of $1.00 to members, $2.00 to non-members.

NORTHERN NEWS

Biological investigations at False River, Ungava Bay

During the months June to September 1958 the estuary of False River, Ungava Bay, was examined in the course of a study of the biology of the amphipods *Gammarus oceanicus* and *G. setosus* and the conditions of their shore environment. This work will be reported in detail when completed. The following is a general account of the area.

The estuary itself can be divided into three components: the seaward arm is a wide shallow area running generally southward to a group of islands and the major tributary stream on the east bank; then follows a narrow deep arm running to the southwest and opening finally into the striking expanse of mud and boulders known as Kohlmeister Lake. This becomes almost completely dry at low tide except for the small freshwater stream of False River proper.

Tidal currents were sufficiently strong to discourage more than one attempt at anchoring a canoe in mid-stream for measuring purposes. The water, which was turbid early in the season, cleared somewhat to give an extinction depth of 4 metres for an improvised Secchi disc. Mud and boulders are the dominant shore materials, and even where sand was found it was covered with a distinct layer of mud 1 to 3 centimetres deep, so that air trapped in the well-sorted underlying material issues in streams of bubbles under the pressure of the rising tide. This observation suggested that deposition of sediment takes place during spring and summer, followed by the resorting of finer materials during the storms of fall. An interesting feature of the shore is the pavement pattern in which smaller boulders occur. Around rocks large enough to resist displacement by winter ice the smaller and somewhat rounded boulders are packed down to produce a generally uniform surface. This does not appear to be due to abrasion but rather to the pressure of ice that is hinged on the large boulders and moves up and down with the tides.

Sharp salinity and temperature fronts were observed moving up and down the estuary, and it seems that the central basin acts as a mixing reservoir receiving water from the north and south arms alternately. The following is a summary of temperature and salinity conditions in late July.

Stations	*Salinity in ‰*	*Temperature in °C*
Seaward parts	22 - 24	5 - 7
Mid-estuary	19 - 21	8 - 11
South Kohlmeister Lake	0 - 17	9 - 17

No evidence was found for deoxygenation in deeper waters; values obtained ranged from 7.1 to 8.1 ml. of oxygen per litre.

The rock of the surrounding country is of low monotonous relief presenting a smooth appearance when viewed toward the north in the apparent direction of ice movement, but at higher levels there are several instances of moraines and water-sorted deposits that suggest raised beaches.

Trees reach their definite limit along a line running northeast from the head of Kohlmeister Lake where there are some quite thick woods. Perhaps the most interesting aspect of the local flora is the extensive development of salt-marsh vegetation. Below the limit of

high neap tides the mud is covered during the summer with a rich green felt of filamentous algae to a depth of 1 centimetre. This striking association was described from the area by Blum and Wilce (Rhodora 60: 283-8, 1958) who found it to contain two species of *Vaucheria* new to North America. On rocky parts of the shore this zone is dominated by *Fucus*. Between the limits of high neap and high spring tides, for a vertical distance of at least 9 feet, there is a strong development of salt grasses where soil exists; this association is particularly well developed in the extensive flats at the head of Kohlmeister Lake. The corresponding zone on the rocky parts of the shore is characterized by bare rocks or pools containing filamentous algae. At the extreme tidal limit there is a sharp line along which many species of plants are present, particularly wild rye and a silver-grey species of willow. Above this line, if trees are present, willows and swamp vegetation merge into a belt of tamarack. On the rocky shore there is an almost complete cover of black lichens.

During the summer only one lemming was seen, but evidence of much previous activity was noticed. Other mammals seen included three mice, one ermine, one silver-grey fox and a young black bear. Seals were occasionally seen throughout the length of the estuary, but the greatest concentrations occur about the seaward parts of False River.

Among the birds ptarmigan were particularly abundant in the vicinity of the base camp on the main eastern tributary of the estuary where two broods were kept under observation during July and until the formation of mixed coveys at the end of August. A family of black duck was reared in the immediate vicinity of the camp and became fully fledged in the first week of August. In contrast to the skerries of the river mouths, the estuary of False River supported few breeding sea ducks, but it did serve later in the season as an assembly point for large numbers of both ducks and Canada geese.

Of particular interest was the occurrence of frogs, tentatively identified as *Rana sylvatica*, in certain shallow pools at the extreme upper limit of spring tides on the salt flats of Kohlmeister Lake. Adult frogs were seen in early July, but were not found later; tadpoles and young frogs, however, were still abundant in September when ice formed on the ponds at night. Large tadpoles kept in captivity at 9° to 14°C. metamorphosed in 6 weeks. These frogs living near the northern limit of their distribution in rather special circumstances would be excellent material for a detailed ecological study.

Some two hundred fish were measured and examined in detail by my companion Mr. P. M. Gillespie who found them generally and heavily infested by gut and body parasites, and during a trip to George River copepod gill parasites were found in 70 per cent of the arctic char. In this connection it was interesting to observe that up to 40 per cent of the two *Gammarus* species on which this work centred were infected with the intermediate stages of as yet undetermined intestinal parasites of vertebrates. A few specimens of *G. oceanicus* were found to contain a single huge, apparently neotenous cestode, which virtually filled the body cavity. *Gammarus* will be worth examining in any investigation of parasite problems of the many fish, seals, and birds that feed on it.

For several seasons the Department of Agriculture has worked in this region assessing the environmental conditions and the responses of a variety of domestic animals and plants. The department now has a sub-station on the southwestern shore of Kohlmeister Lake, and the writer wishes to acknowledge gratefully considerable help from Mr. R. I. Hamilton, officer in charge of the station. Thanks are also due to Mr. Hodgekinson, Northern Service Officer, and Mr. Ploughman of the Hudson's Bay Company, Fort Chimo. Substantial supplies were kindly donated for this journey by The Imperial Tobacco Company of Canada Ltd., C.I.L., Fry-Cadbury Ltd., and Nestlé's Ltd. The investigation was financed by grants from the Carnegie Arctic Research Fund and the Arctic Institute of North America.

R. J. MacIntyre

New polar ship

On January 27, 1959 the M. S. *Perla Dan* underwent her speed trials. She has been built for J. Lauritzen, Copenhagen to the highest class of Lloyd's, with reinforcements corresponding to the Finnish ice class A 1, by A/S. Pusnes Mekaniske Verksted, Arendal, Norway. The powerplant is a B. and W. diesel engine, Type 735 — VBF — 62 of 2020 IHP. It drives a variable-pitch propeller made by Aalborg shipyard, which gives the ship manoeuverability for ice navigation.

Engine and accomodation are placed aft and the living quarters are very spacious for the size of the vessel. One-man cabins are provided for all on board. The mess rooms have been decorated by young Danish artists, as has been done in the other ships cf the firm.

The navigation equipment is fully modern and includes radar, gyro compass, automatic pilot, echo sounder, Decca, and radio for voice and code. In ice the ship can be navigated from a crow's nest at the top of the foremast.

The boat has a displacement of about 2,700 tons, an overall length of 275 ft., a beam of 42½ ft., and a draft of 19¾ ft. Its speed fully loaded is approximately 12.5 knots. The holds have a capacity of about 132,000 cu. ft. of grain and are accessible through four hatches, which can be combined into two of 58-foot length each to accommodate exceptionally long cargo. The holds are served by eight derricks of 5-ton capacity and one of 30-ton capacity.

An interesting, well-illustrated booklet of 24 pages describing the inception of the fleet of polar vessels and giving technical details of its various units has recently been published by the J. Lauritzen Lines, Copenhagen, Denmark.

Note on cover picture

Professor Hessler writes: the picture was taken at 2200 local time on February 23, 1957 on the campus of the Univ. of Alaska, College, looking almost due north. The foreground illumination is due to street lights. It is very unusual to have a form of such intensity rising directly in the north. Within a minute after reaching this intensity the upper part tilted to the left and developed a very prominent rayed structure.

There is very close correlation between earth-current disturbances and auroral displays. I have an alarm in my bedroom actuated by the earth-current recorder and before retiring set up the camera and lay out warm clothing; all I lack is a fireman's pole for a rapid exit into the arctic night. Usually the most photogenic displays correspond to an

auroral break-up, which may last only 3 or 4 minutes, and unfortunately the signal system does not anticipate the phenomenon.

Technical details: Rolleiflex with cable release on firm tripod; 10 sec. at f: 3.5; Tri-X developed 20 min. in Microphen; printed on No. 4 paper.

GEOGRAPHICAL NAMES IN THE CANADIAN NORTH

The Canadian Board on Geographical Names has adopted the following names and name changes for official use in the Northwest Territories and Yukon Territory. For convenience of reference the names are listed according to the maps on which they appear. The latitudes and longitudes given are approximate only.

Chart 5348, Hopes Advance Bay and Approaches
(Adopted April 3, 1958)

Lookout Island	59°34′N.	69°19′W.	
Young Island	59°29′	69°24′	
Alle Island	59°23′	69°33′	
Coffin Islet	59°23′	69°34′	
Nanertak Island	59°19′	69°09′	
Barrier Shoals	59°32′	69°10′	
Black Rock	59°23′	69°21′	
Sawtooth Reef	59°25′	69°10′	
Takiyok Reef	59°23′	69°07′	
Sentinel Reef	59°16′	68°49′	
Merganser Cove	59°21′	69°40′	
Funnel Cove	59°18′	69°37′	
Pointe De Villiers	59°20′	69°17′	
Takiyok Point	59°19′	69°16′	not Pointe De Villiers
Ikattok Bay	59°11′	69°16′	not Baie Turquetil
Altered application			
Low Islands	59°31′	69°21′	

Blackwater Lake 96 B
(Adopted April 3, 1958)
Altered application

Rivière Poisson-Bleu	65°00′N.	123°40′W.

Wellington Channel, 58 NW. and 58 NE.
(Adopted May 1, 1958)

Eleanor River	75°23′N.	94°00′W.
Rookery Creek	75°23′	95°49′
Snowblind Creek	75°13′	93°33′
Sophia Lake	75°07′	93°34′

M'Clure Strait, 98 NE., 88 NW., and 88 NE.
(Adopted May 1, 1958)

Shellabear Point	74°51′N.	113°20′W.	not Shellabeer Point

Cambridge Bay, 77 SW. and 77 SE.
(Adopted May 1, 1958)

Johansen Bay	68°34′N.	111°05′W.	
Nakyoktok River	68°37′	110°52′	
Mackenzie Creek	68°36′	111°21′	not Mackenzie River

Horton Lake, 96 O
(Adopted May 1, 1958)

Horton Lake	67°30′N.	122°23′W.
Raymond Lake	67°07′	123°56′
Little Lake	67°13′	123°50′
Estabrook Lake	67°55′	123°45′

Buffalo Lake, 85 B
(Adopted May 1, 1958)

Pine Point (settlement)	60°47′N.	114°18′W.
Needle Lake	60°20′	114°25′

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